

***Precipitation-Runoff Relationship  
at the Upper Basin of the  
Virgin River, Utah.***


by

Dr. Gustavo E. Diaz  
and  
Tarmizi Ismael

Dept. of Civil Engineering  
Colorado State University

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Fort Collins, Colorado 80523

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## **1.0 INTRODUCTION**

### **1.1 Purpose of the Study**

The purpose of this study is to assess the spatial variability of mean-annual flows in Zion National Park (Zion) and its surrounding areas within the Upper Basin of the Virgin River. The drastically changing topographical, geological, and climatological conditions yield significant changes in the watersheds' water-yield. Changes in water-yield are significant not only among different basins, but also along the course of a given stream.

The study implements a computational methodology for the estimation of long-term mean annual discharge at ungaged river sites in the Upper Basin of the Virgin River, with special consideration to the North Fork of the Virgin River. Estimates of mean annual discharge at different river locations are necessary to support biological and channel processes studies being conducted at Zion and adjacent areas.

Findings from this study should be used in conjunction with other hydrological information provided by two previous reports, Diaz (1992) and Diaz (1993). In particular, estimates of mean-annual flows at ungaged sites makes possible to calculate their duration based on the parametric flow duration analysis presented in the first report, Chapter 6.

### **1.2 Scope of the Study**

Given the limited number of stream gages with long and reliable records in the Zion area, it was decided to estimate annual streamflows at ungaged locations based on main basin characteristics, climatic data and historical streamflow data in the region. The methodology will be based on relating statistically the variability of the runoff-precipitation ratio at observed sites, to the regional physical and hydro-meteorological information indicated above. Once these statistical relationships are defined, estimates of annual discharge at ungaged sites can be obtained by just knowing topographic and climatic factors at the site of interest.

Geographic Information Systems (GIS) became an extremely valuable tool during the computational process as described later. The inherently spatial characteristics of practically



all data used in this study made the GIS an ideal tool for manipulating, analyzing and displaying data and results. GIS was used to perform repetitive spatial analysis accurately and speedily.

The report is organized as follows: Section 1 introduces the reader to the purpose and objectives of the study. Section 2 locates geographically the study area and provides brief information about the principal basin features and water uses. Section 3 provides an overview of the most relevant techniques implemented by other authors to estimate precipitation-runoff relationships. Moreover, it introduces the methodology utilized in this study. Section 4 describes the merits of the GIS application developed for this study and the spatial analysis procedure. Section 5 presents and discusses existing surface runoff and precipitation records within the study region. The difference between exiting and natural flow conditions is also discussed in Section 5. Section 6 focuses on the transfer of information among precipitation stations within the study area in order to extend and/or complete annual precipitation records. The areal distribution of annual precipitation is also analyzed in this section. Finally, Section 7 presents the computation of the watersheds' water-yield, and more specifically, the precipitation-runoff relation for the North Fork of the Virgin River. It also provides an example of the estimation of mean annual flows at ungaged sites. The report is concluded with literature references in Section 8, and appendixes I and II, containing additional results of the regression analysis and annual flow records at the U.S. Geological Survey gaging sites, respectively.



## **2.0 STUDY AREA**

### **2.1 Location**

The study area is bounded by latitudes N37°00'00" and N37°37'30", and longitudes W113°15'00" and W112°22'30". It constitutes the headwaters of the Virgin River and Kanab Creek, located in the South-Western corner of the State of Utah. The whole area is covered by thirty four 7.5-minutes (1:24,000 scale) U. S. Geological Survey (USGS) quadrangle maps, comprising an area of 1,290 square miles (825,600 acres).

The study area includes several hydrological subareas as shown in Figure 1. They are, from east to west: Kanab Creek, East Fork of the Virgin River (EFVR), North Fork of the Virgin River (NFVR), North Creek, Virgin River, La Verkin Creek, and a small portion of Ash Creek. A comprehensive description of the hydrological subareas as well as the stream network and flow characteristics can be found in a previous report by Diaz (1992).

Figure 1 also shows the location of Zion within the Upper Virgin River Basin. The park covers a total area of 231.3 square miles, distributed as follows: 35% within the NFVR subarea, 22% within the North Creek subarea, 15% within the La Verkin Creek subarea, 12% within the EFVR subarea, 12% within the Virgin River subarea and the remaining 4% in the Ash Creek subarea.

### **2.2 Principal Basin Features**

The Virgin River originates in the Colorado Plateau physiographic province and flows to the Basin and Range province. The Virgin River, the main water course, drains the upper watersheds in the study area. The river is formed by two major tributaries, the East and North Forks of Virgin River, as well as several other smaller tributaries. The East and North Forks flow in a north-east to south-west direction for approximately 52.17 and 44.21 river miles respectively. The East and North Fork of the Virgin River and Kanab Creek are perennial, whereas other tributaries of the Virgin River range from perennial to ephemeral.

The physiography of the region is characterized by very special features, with Zion as the main attraction. The Virgin River has cut its way through massive rock formations,



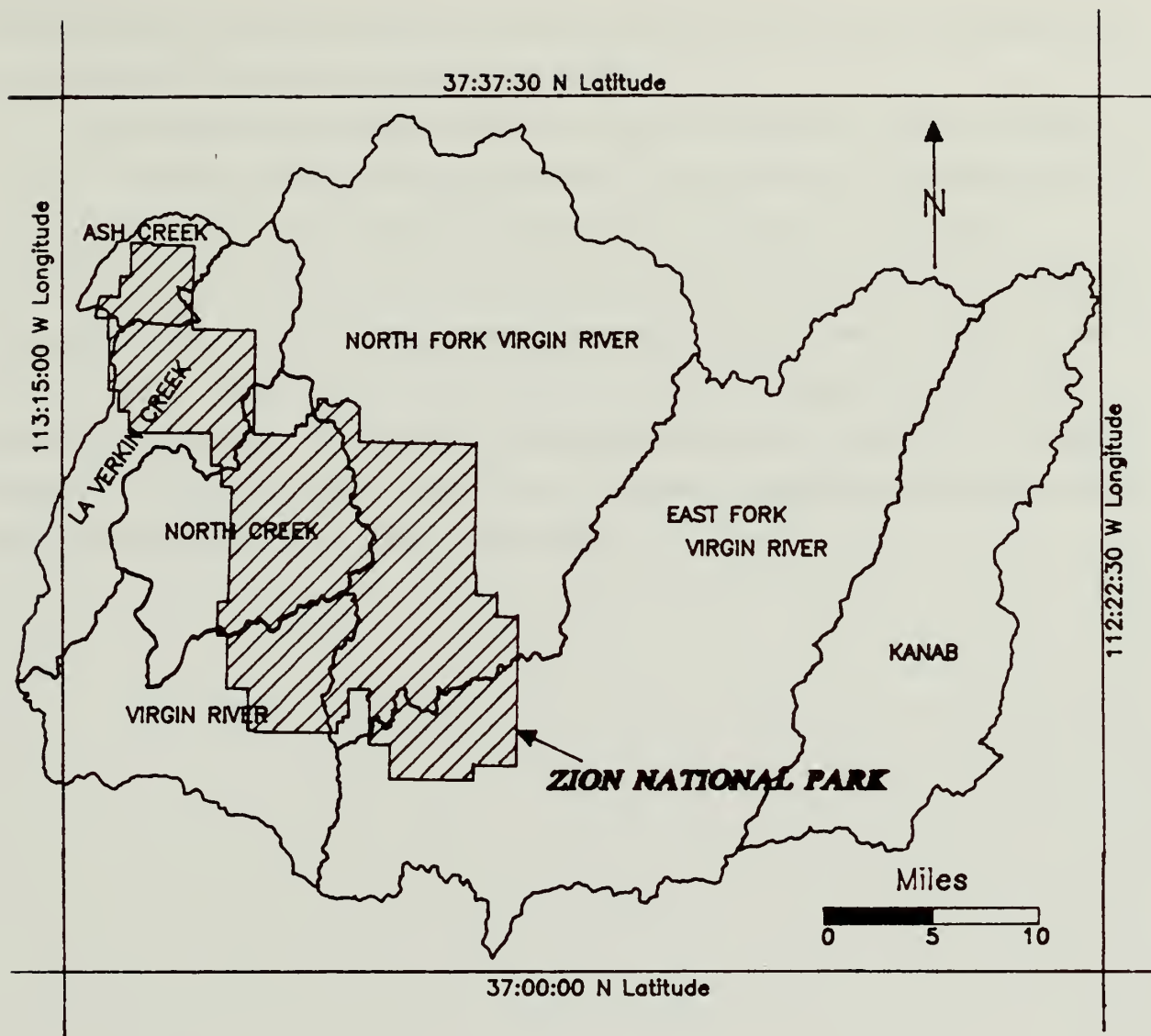


Fig.1 The Study Area, Showing Hydrologic Subareas and Zion National Park

ranging from approximately 3,400 feet in elevation at the lowest point within the study area, to over 10,000 feet in elevation at the upper ridges. The ample change in floor elevation creates considerable spatial variability of the hydro-meteorological conditions in the basin. For instance, a U.S.G.S. study (1985), depicts the study area as a region with annual precipitation ranging from 10 to 30-plus inches per year and precipitation increasing in the north-easterly direction. Similarly, annual runoff is shown to vary from 0.1 to 5 inches per year, with the larger yields corresponding to the high elevation areas. These figures,



although general in nature, provide a preliminary indication of the rainfall-runoff ratios that can be expected in the area of Zion National Park.

The primary uses of surface water in the region are irrigation, industrial and public supply. The earliest water rights were adjudicated in the late 1800's. The majority of the water rights in the region correspond to irrigation rights. There are also numerous stockwatering and domestic users, which according to the State of Utah - Division of Water Rights, the quantity of water they represent is relatively small compared to irrigation water. Water diversions occur directly from the main water courses cited above as well as from small tributary sources. Unfortunately, no strict enforcement of the irrigation water rights exist in the Upper Basin of the Virgin River. This situation complicates assessing the effect water diversions have on the streams natural regime.



## **3.0 RAINFALL-RUNOFF RELATION**

### **3.1 Previous Work Related to the Study**

The spatial and temporal variability of surface water in the United States has been thoroughly investigated by several authors, mainly by the U.S.G.S. Surface water investigations have been extensively used for the development and management of water resources. Most studies are regional in nature, relating discharge to catchment physiography and climatic variables. Some of these investigations have the potential to estimate annual flows at ungaged river sites. The relation between annual precipitation and runoff can be carried one step further, by estimating the percentage of rainfall to runoff. This ratio condenses, in a single number, multiple and complex physical processes that take place in a basin from the occurrence of precipitation to the appearance of surface runoff at the catchment outlet.

In order to analyze annual runoff, Horn (1988), used step-wise regression analysis to relate the mean and standard deviation of annual flows from 124 stream gages in Idaho. Basin characteristics such as drainage area, mean annual precipitation and percent forest cover were used with the data regionalized geographically. Equations and maps were developed to estimate flow statistics at ungaged locations. Using also a regional approach, Waylen and Woo (1982), fitted annual flows from the Fraser River catchment in British Columbia by using the Gaussian distribution. The spatial variability of the parameters of the distribution were determined in a regional basis. Parameters at ungaged locations could then be predicted using the latitude and longitude of the basin centroids, and ultimately generate flows of various return periods.

Gan et al. (1990), developed predictive equations for the mean and coefficient of variation of annual streamflows against a variety of catchment rainfall and physiographic parameters. They concluded that only catchment area and annual rainfall statistical parameters have significant explanatory value, and that additional catchment physiographic variables do not improve the estimation. The Utah Division of Water Resources (1983, pp.57), used the Area-Altitude Runoff Method to estimate runoff-precipitation relations for



forecasting summer water supply in the Upper Virgin River Basin. This method correlates two adjacent drainages, one where the runoff is known. The method assumes that the relationships between precipitation and runoff are similar for two adjacent drainage areas.

In works related to this study, Emmert (1979) and Heitz (1981), derived procedures for estimating mean annual flow using the runoff coefficient. The method was used to survey the existing hydroelectric potential in the Pacific-Northwest region. The computation of the runoff coefficients was based on gaged flows and mean annual precipitation.

### **3.2 Definition of Runoff Coefficient**

The term "runoff coefficient" has been defined differently by many authors. For instance, Chow et al. (1988) defines runoff coefficient for single rainfall-runoff events as the ratio of the peak rate of direct runoff to the average intensity of rainfall in a storm. Customarily, it is also being defined as the ratio of runoff to rainfall over a given period of time. This study defines runoff coefficient as the ratio of surface runoff (excess rainfall) to the total volume of precipitation collected in the basin, both measured during the same time interval. The observation period adopted for this study is the annual water cycle, from October 1 to September 30, as established by the U.S.G.S.

The runoff coefficient depends upon many factors such as basin size and slope, percent imperviousness and ponding characteristics of the surface. The rainfall infiltration rate is affected by the antecedent moisture condition of the soil which in turns is also influenced by the runoff coefficient. Other factors that influence the runoff coefficient are rainfall intensity, water table proximity, degree of soil compaction, porosity of the subsoil, vegetation and depression storage (Chow et al.,1988), etc. This study focuses on the most critical factors affecting the rainfall-runoff relationship. Based on results from previous studies, the following explanatory variables are adopted,

**Drainage Area:** The quantity of discharge is a function of the basin size. Many empirical precipitation-runoff equations use drainage area as the main descriptive parameter. The rational formula is a classic example.

**Precipitation:** Precipitation in the Zion region is characterized by large annual and seasonal variations. This study uses annual precipitation (irrespective



of seasonal changes) as a simple and comprehensive index of precipitation. Several meteorological stations collect precipitation data in the region, from which maps of Normal Annual Precipitation (NAP) can be constructed for the study area .

**Basin Elevation:** Altitude is a simple index through which complex processes affecting runoff can be indirectly evaluated. For instance, the combined effect of soil type, precipitation, radiation, temperature, evaporation, vegetation and snow melting rate can be somehow interpreted by basin elevation.

**Soils and Geology:** Geologic formations and highly faulted zones have much of the precipitation disappear into fissures and underground channels. These geologic features are difficult to quantify, making the delineation of zones with high and low infiltration rates a difficult and time consuming task.

### 3.3 Mean Areal Precipitation and "K" Values

The amount of precipitation a catchment receives during any year (or period of years) will be estimated from NAP (isohyetal) maps. An isohyetal map provides interpolated areal values of precipitation based on recorded precipitation at the gaging sites. The isohyetal method is perhaps the most accurate approach for determining average precipitation for an area. The computational procedure utilized in this study for generating isohyetal maps is described later in Section 4.

Figure 2 shows a hypothetical watershed boundary with lines of equal precipitation depth (isohyets) crossing the region. Also shown in Figure 2 is the river location at which the runoff coefficient will be determined, indicated as site of interest, and the catchment boundary contributing runoff to that specific location. The procedure is simple and includes the following steps:

1. Generate mean-annual precipitation map for the study area.
2. Delineate catchment contributing runoff to site of interest.
3. Overlay isohyetal map onto the catchment boundary map.
4. Determine area of influence,  $A_i$ , for each isohyet of magnitude  $P_i$



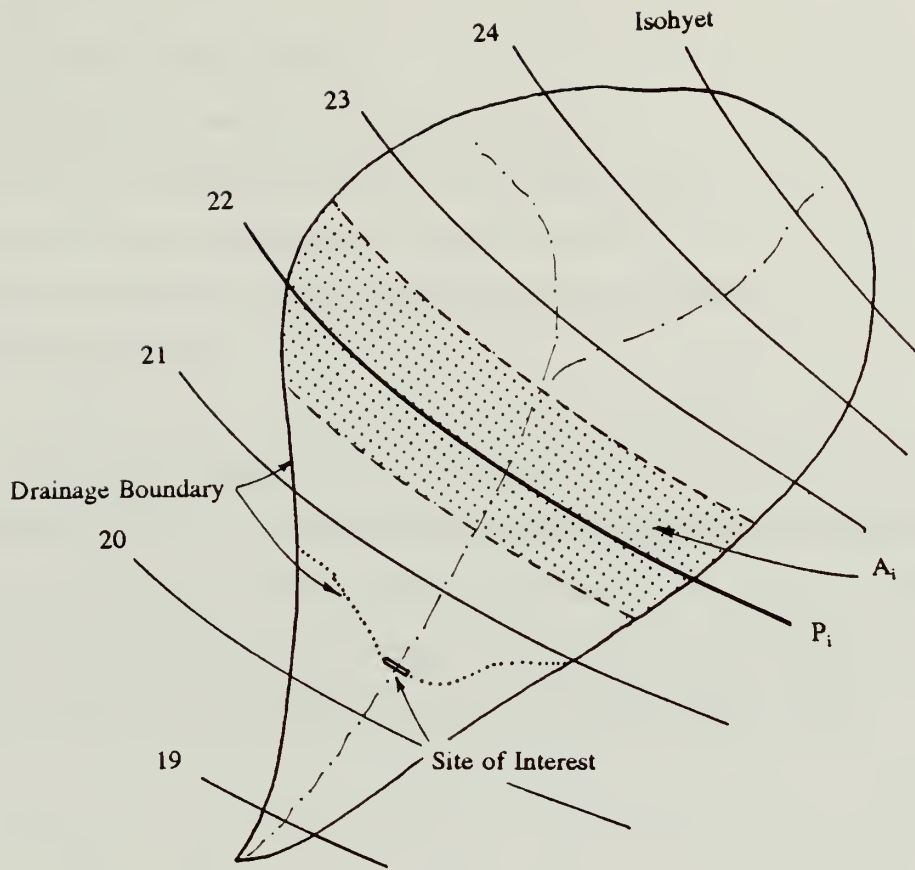


Fig.2 Drainage Boundary with Isohyet Lines

5. Compute precipitation input by integrating area and precipitation from each subarea

$$\sum_{i=1}^{N_I} A_i P_i$$

6. Compute surface runoff,  $R$ , at catchment outlet during the observation period used to generate the isohyetal map.
7. Compute runoff coefficient,  $k$ , at site of interest.

Mathematically, the runoff coefficient is expressed by,

$$k = \frac{R}{\sum_{i=1}^{N_I} A_i P_i} C_f \quad (1)$$



where:

- $k$  runoff coefficient [dimensionless]
- $R$  annual discharge, expressed in volume units [ac-ft]
- $A_i$  portion of the drainage area associated with isoline  $i$  [mi<sup>2</sup>]
- $P_i$  precipitation depth corresponding to isohyet  $i$  [inches]
- $N_I$  number of isohyets ( $A_i$  zones) within the catchment of interest
- $C_f$  units conversion factor

When  $R$ ,  $A_i$  and  $P_i$  are expressed in the units indicated above, the units conversion factor  $C_f$  adopts the value 0.0188. The runoff coefficient can be computed for a single water-year, denoted as  $k$ , or average for a multiple years, and indicated as  $\bar{k}$ . In fact, the runoff coefficient can be defined for any time interval, provided that the same period of record is being used to evaluate annual precipitation (isohyetal map) and surface runoff.



## **4.0 GEOGRAPHIC INFORMATION SYSTEM**

### **4.1 Role of Geographic Information System**

With the advent of Geographic Information Systems (GIS) in the field of water resources, a vast number of studies have been incorporated a GIS to rainfall-runoff modeling. GIS has been described as a powerful and efficient tool for many areas of investigation dealing with environmental and natural resources systems (Tan, et al., 1991). This technology has developed rapidly and it is now accepted by hydrologists as a valuable tool to evaluate and analyze hydrological processes.

An example that coincides with this report was the work by Stuebe and Johnston (1990) using the Geographic Resources Analysis Support System (GRASS), a raster based GIS, to model rainfall-runoff for six watersheds of diverse physiographic characteristics and land cover. GRASS was used for all phases of the modeling process, including watershed delineation and routing of runoff. Results from the GIS modeling were compared to results from a conventional (manual) approach. The GIS methodology was proved advantageous over manual methods when study areas are large or numerous, runoff is modelled repetitively, alternative land cover scenarios are explored, or a digital database already exists for the area. Our case study satisfies the conditions to effectively utilize a GIS.

Two different GIS packages were utilized during the study, ATLAS-GIS and IDRISI. ATLAS-GIS (1992), referred hereafter as ATLAS, is a PC-based GIS developed by Strategic Mapping's Inc. It is a desktop GIS that combines the extensive analytical and presentation capabilities of main-frame mapping software with the ease and low cost of desk-top mapping. ATLAS uses a vector data structure and thereby admits the advantages and disadvantages of vector systems. ATLAS has strong digitizing capabilities, including a continuous (direct) on-screen update of the digitizing process. ATLAS was used in this study exclusively to create thematic layers by manual digitalization.

The other GIS package, IDRISI (Eastman, 1992), is also a PC-based GIS introduced in 1987 by the Graduate School of Geography at Clark University. IDRISI is a relatively simple and inexpensive package that allows the user to create attractive maps and develop



useful applications. IDRISI is essentially a raster-based GIS that has some powerful and sophisticated analysis capabilities. It was used in this study for data manipulation, data analysis and display of results. Even though IDRISI has limited vector capabilities, it is one of a few GIS packages that can store and display raster and vector images. Successive upgrades (Version 4.0 used in this study) have extended its capabilities to almost 100 program modules. In addition, IDRISI has a set of peripheral modules for interfacing with other GIS packages, spreadsheets and database management systems.

## **4.2 Maps Characteristics**

Some of the GIS thematic layers used in the study were originally developed for a previous study as reported by Diaz (1992). Existing layers included:

- main watersheds boundaries,
- rivers drainage network,
- Zion National Park boundaries,
- location map of streamflow gaging stations.

The digital maps were created using a vector format in ATLAS. These digital maps were also required in raster format. Then, the conversion process indicated below was implemented:

1. Vector files created by ATLAS were converted into ASCII files using the ATLAS <Import/Export> utility.
2. Auxiliary programs translated the ASCII files from step 1 into point, line and polygon files (along with their associated documentation files) compatible with IDRISI's vector format.
3. The <INITIAL> and <POLYRAS> functions of IDRISI were used to convert the vector files from step 2 into raster images.

In order to have the same pixel (picture element) resolution and geographic location for all images, the following map characteristics were adopted:

Number of rows: 200

Number of columns: 250

Minimum X: 243,196. m.



Maximum X: 378,733. m.

Minimum Y: 4,098,859. m.

Maximum Y: 4,188,701. m.

These map characteristics produced images with a pixel resolution of 544.33 m by 451.47 m, considered reasonable for the purpose of the study. Vector files had the same map characteristics, therefore they could be displayed simultaneously with a raster image that had the same number of rows and columns.

Additional thematic layers were created specifically for this study. They are:

- location map of precipitation gaging stations,
- isohyetal maps of annual and multiple year precipitation,
- subarea watersheds contributing to specific river locations,
- simplified geologic map of the Zion Park region.

The delineation of drainage areas contributing to specific river sites were digitized from the topographic maps indicated in a previous study (USGS, 1:24,000 scale). The new layers were created as an extension of the existing layers. Digitizing errors due to uncertainty on the ground location of control points were evaluated before digitizing the boundary lines. Errors were kept below 0.01 cm to minimize the inaccuracy of the GIS products.

### **4.3 Spatial Analysis**

The implemented GIS facilitated the preparation of basic data files, performed spatial analysis of spatially referenced data, and displayed and examined results leading to the determination of the variability of runoff coefficients in the Zion region. The flow-chart in Figure 3 summarizes the main stages in the implementation of the GIS. Topographical and meteorological information were collected and processed simultaneously, before the spatial analysis was carried out by IDRISI. The multistage GIS spatial analysis procedure is depicted in Figure 4.

The first step in Figure 4 utilizes the <OVERLAY> function to superimpose two raster images. The first image contains a regional isohyetal map identified as layer [A]. The second image contains the map of the watershed contributing runoff, indicated as layer [B].



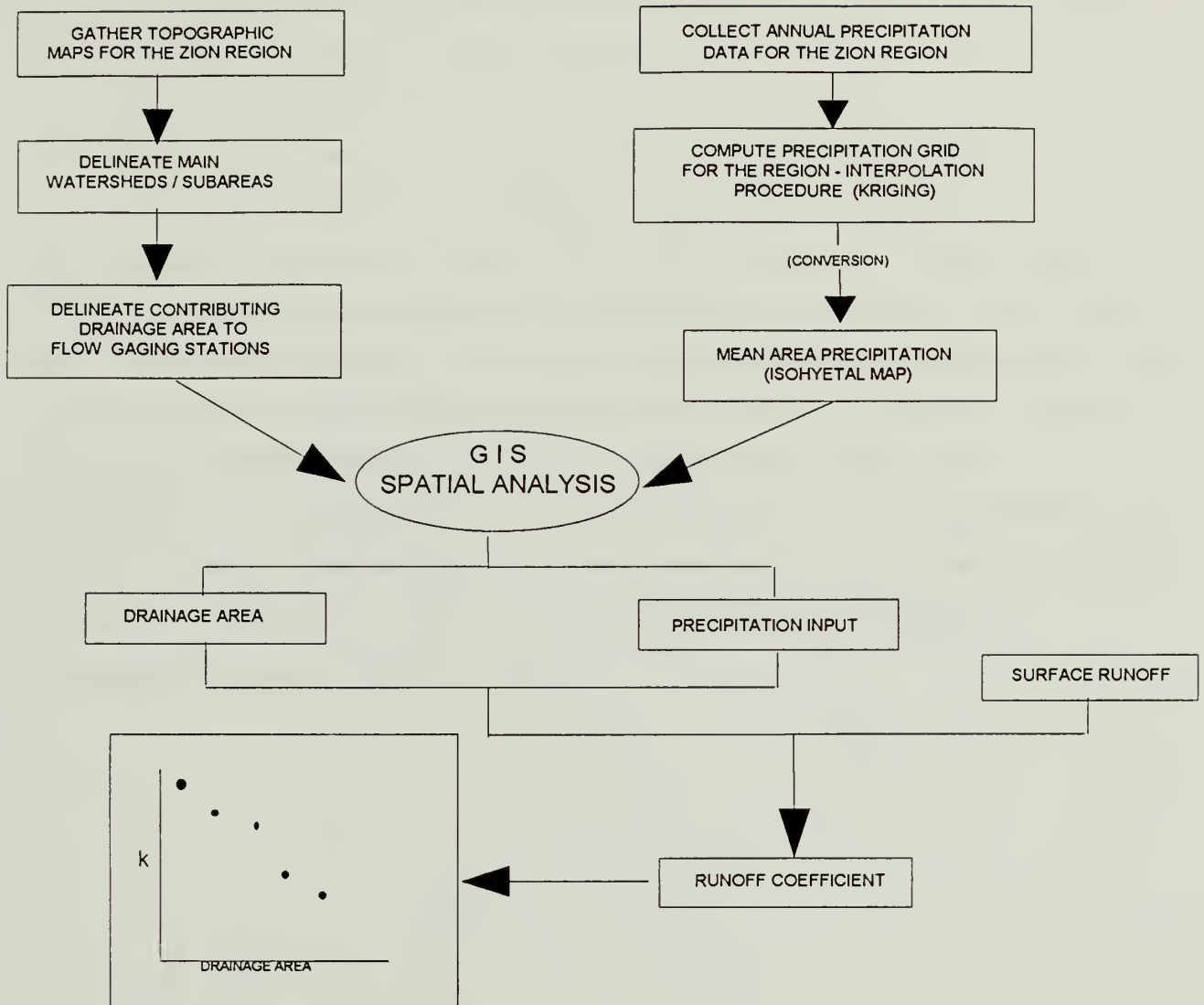


Fig.3 Flow-Chart for Generating Runoff Coefficient Curve

The overlay yields a new raster image identified as layer [C]. Computationally, this first step involves a masking procedure designed to extract the desired information from the precipitation layer. A binary mask establishes a value of "1" inside the watershed region, and "0" outside. Application of the mask to the isohyetal map and utilization of the <OVERLAY> function from IDRISI results in an image containing the spatial variability of precipitation within the watershed of interest.



The second step involves the <AREA> function which computes the surface area for each isohyet zone (see  $A_i$  in Figure 2), and the surface area outside the basin boundary. This step creates two outputs, an image file [D] where each pixel's z-coordinate has the value of the drainage area (in  $\text{mi}^2$ ) corresponding to the zone it belongs; and an attribute value [.VAL] file, denoted as [E], that summarizes the results of the computation.

Next, the <OVERLAY> function is run twice. First, to create the intermediate map [F] by masking image [D] with the binary layer [B] that delineates the subbasin. Second, to overlay the precipitation layer [C] and the surface area layer [F] to obtain the final image [G]. The z-coordinate values in [G] represent volume of precipitation (in inches- $\text{mi}^2$ ). These values are obtained by selecting the "multiply" operator in the <OVERLAY> function, which then multiplies corresponding pixels from the two images. Finally, the <EXTRACT> function generated an attribute value file [H] from the image file [G]. [H] itemizes volumes of input precipitation per isohyet zone from where the total for the basin is computed. A batch file was written to automate the execution of the sequential computational procedure indicated in Figure 4.



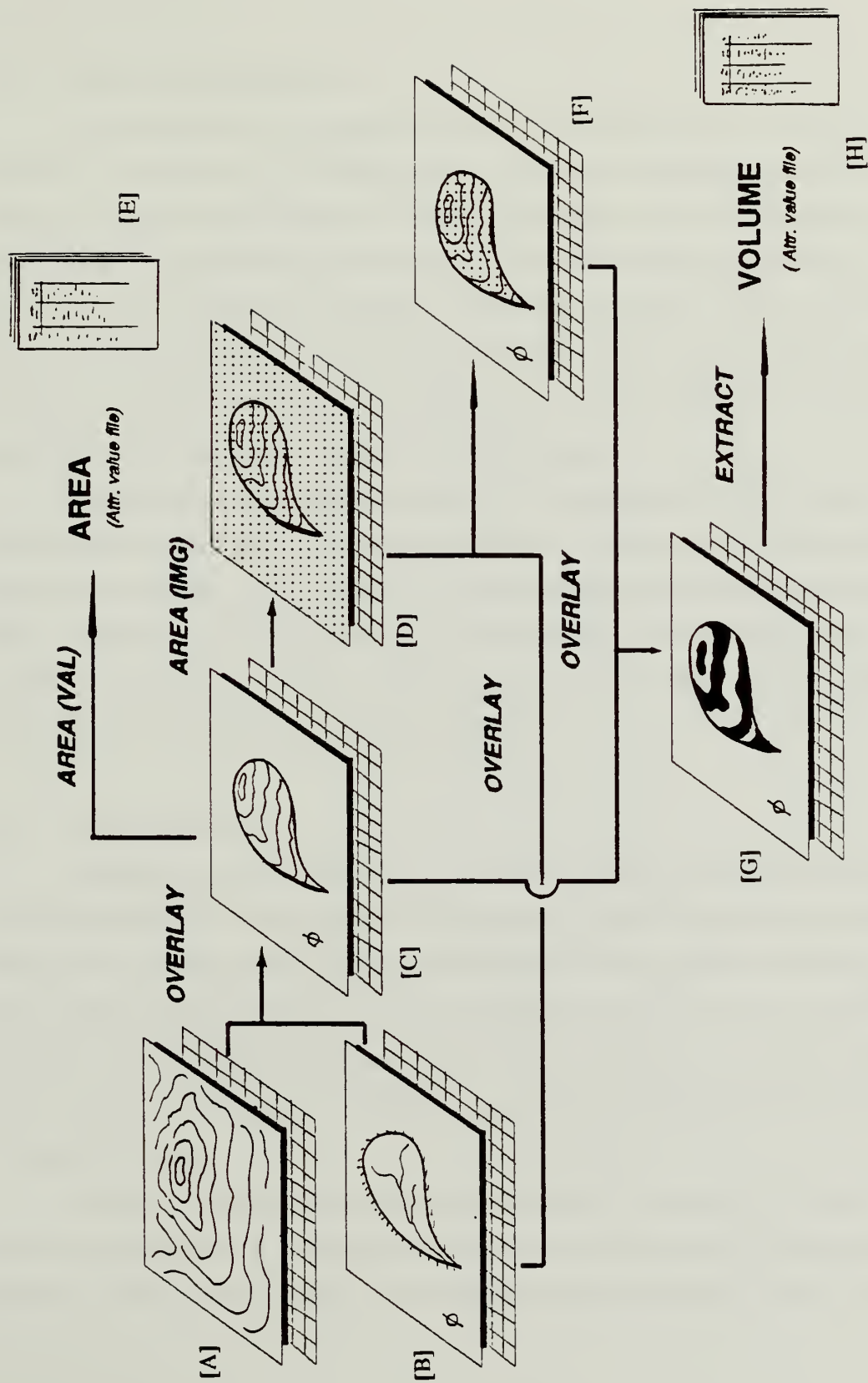


Fig.4 GIS Spatial Analysis Procedure



## **5.0 STREAMFLOW AND PRECIPITATION DATA**

### **5.1 Surface Runoff Records**

Streamflow data for the gaging stations were obtained from the USGS CD-Rom database. The location of the gaging stations , active and discontinued, are indicated in Figure 5. All gages are located in the same hydrologic region, the Upper Basin of the Virgin River, except for the station at Site (1), located in the Kanab Creek basin. Flow data consist of annual discharge, expressed in volume units (acre-feet). Table 1 lists the stations along with their geographical location, periods of flow record, water yield, and some basic statistics. The reader is referred to a previous report by Diaz (1992) for a comprehensive description of the streamflow network in the Zion region.

The drainage areas contributing runoff to the gaging sites listed in Table 1 were recomputed using the GIS. Values given in Table 1 are a revision of those provided in a previous report (Diaz, 1992 - Table 3.). Differences in surface area range from 0.1% to 5.8% between the values computed by the GIS and those reported by the USGS. The only exception is site (5), E.F. Deep Creek near Cedar City, for which the GIS computed an area 28% larger than the one indicated by the USGS.

### **5.2 Water Depletions**

Practically all hydrologic subareas in the Upper Basin of the Virgin River are subject to water depletions. Water depletions are caused by cropland and wetland consumptive use, domestic use, reservoirs evaporation, transbasin diversions and other minor uses. Because of water depletions along the rivers, flows registered at the gaging stations are indicative of "existing" flow conditions rather than "natural" flow conditions. In order to estimate natural flows, water losses caused by anthropogenic activities should be quantified and added to the existing flow regime.

The quantification of water depletions presented in this section is based on two sources of information: a hydrologic inventory of the Virgin River (Utah Division of Water Resources, 1983), and a personal communication with the Division of Water Rights of the



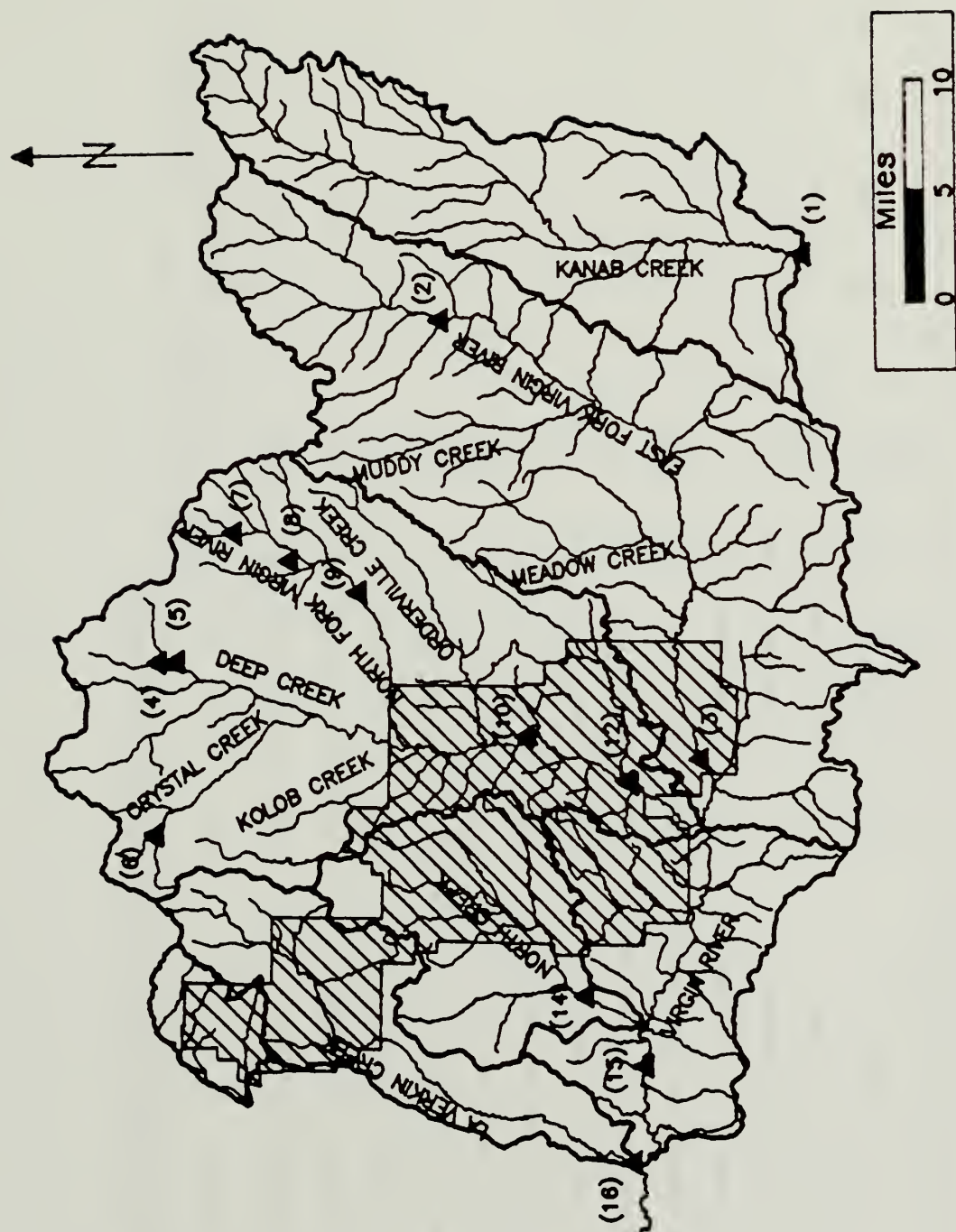


Fig.5 River Network and USGS Streamflow Gaging Stations



Table 1. Streamflow Gaging Stations Used in the Study, Basic Statistics

Site No.	USGS No.	Station Name	Latitude	Longitude	Elevat. [ft]	Drainage Area [mi <sup>2</sup> ]	Period of Analysis		Mean Annual Flow				
							19__	No.Yrs	Measured Flows [cfs-yr] [ac-ft]	Natural Flows [cfs-yr]	Diff. (%)		
(1)	09403600	KANAB CREEK near KANAB	37:06:02	112:32:50	5060.	192.6	79-92	14	13.7	9,884.	15.0	10,819	8.6
(2)	09404450	E.F. VIRGIN Rv. near GLENDALE	37:20:19	112:36:13	5900.	74.3	67-92	26	19.1	13,786.	19.4	14,051	1.9
(3)	09404900	E.F. VIRGIN Rv. near SPRINGDALE	37:09:51	112:57:28	3940.	347.8	92	1 (*)	49.9	36,190.	52.9	38,202	5.3
(4)	09405200	DEEP CREEK near CEDAR CITY	37:31:18	112:53:01	7680.	6.4	88-92	5	1.7	1,209.			
(5)	09405250	E.F. DEEP CREEK near CEDAR CITY	37:30:35	112:52:58	7640.	9.4	88-92	5	2.8	2,053.			
(6)	09405300	CRYSTAL CREEK near CEDAR CITY	37:31:20	113:01:25	8320.	10.1	57-61	5	7.1	5,237.			
(7)	09405400	N.F. VIRGIN Rv. near GLENDALE	37:28:22	112:46:40	7530.	5.7	73-78	6	5.0	3,624.	5.3	3,800	4.6
(8)	09405420	N.F. VIRGIN Rv. blw BULLOCK CANYON	37:25:06	112:47:59	6420.	29.1	75-84	10	19.6	14,307.	21.0	15,207	5.9
(9)	09405450	N.F. VIRGIN Rv. abo. ZION NARROWS	37:23:26	112:49:30	6000.	44.3	79-84	6	25.7	18,546.	27.4	19,808	6.4
(10)	09405490	N.F. VIRGIN Rv. above BIG BEND	37:16:43	112:56:38	4400.	287.7	92	1 (*)	71.67	51,940.	75.4	54,516	4.7
(12)	09405500	N.F. VIRGIN Rv. near SPRINGDALE	37:12:35	112:58:40	3970.	343.4	26-88	62	104.5	75,718.	108.3	78,294	3.3
(14)	09405900	NORTH CREEK near VIRGIN	37:14:14	113:09:01	3680.	95.1	86-92	7	6.8	4,901.			
(15)	09406000	VIRGIN RIVER at VIRGIN	37:11:53	113:12:22	3440.	939.5	10-71 79-92	76	201.0	145,633.	209.8	153,634	5.2
(16)	09406150	LA VERKIN CREEK near LA VERKIN	37:12:17	113:17:03	3040.	96.3	86-91	6	8.5	6,105.	11.1	8,032	24.0

(\*) Mean Annual Flows correspond to only one water-year, (1992).



State of Utah (Olds, 1993). Additionally, acreage under irrigation reported by the USGS (Water-Years books for the State of Utah) was considered. As indicated by Olds (1993), water depletions are rough estimates, since "... there is no way of knowing whether the water users exceed their diversion right or the annual irrigation duty".

The Utah Division of Water Resources computes water depletions based on the croplands potential consumptive use (PCU) using the modified Blaney-Criddle method. PCU in combination with soil moisture and effective precipitation determine the actual consumptive use for the crops. Annual consumptive use for each crop is multiplied by the acreage of the crop type to obtain the total water depletion in agricultural use. Small water depletions for municipal use were not considered in the water budget. Table 2 provides the main estimated depletions in the study area. The calculated depletions are reasonable estimates given the limited amount of data available. The dashed lines in Table 2 indicate unavailable data.

Table 2. Estimated Annual Water Depletions

Location (site)	Water Depletions	
	[Ac-Ft]	[cfs-yr]
above (1)	935	1.29
above (2)	265	0.37
between (2) and (3)	1,747	2.42
above (4)	---	---
above (5)	---	---
above (6)	---	---
above (7)	176	0.24
between (7) and (8)	724	1.00
between (8) and (9)	362	0.50
Kolob Reservoir	450	0.62
between (9) and (10)	864	1.20
Springdale Canal	4,700	6.50
between (12) and (15)	3,413	4.72
above (14)	---	---
above (16)	1,927	2.67

Additionally, Figure 6 shows a sketch of the Upper Virgin River network indicating the location (river reaches) of water depletions in the region. The estimated water depletions are substantially less than the duty of irrigation water. The later is dependant upon the



length of the frost free period, effective annual rainfall, evapotranspiration of crops, application losses, etc. For instance, the duty of water can oscillate between 3 to 6 ac-ft of water per acre of land under irrigation according to the State Engineer. Four ac-ft per acre annually is a reasonable value for the Zion region. On the other hand, depletions were estimated to be less than 2.5 ac-ft of water per acre of irrigated land. It is assumed that the difference between the water duty and the actual consumptive use returns to the stream almost immediately given the proximity of the irrigated lands to the stream. Similarly, it is assumed that possible diversions of water beyond what is required return to the stream in the same manner. In general, water depletions indicated in this section should be considered as lower bound (minimum) estimates of the water depletions in the region.

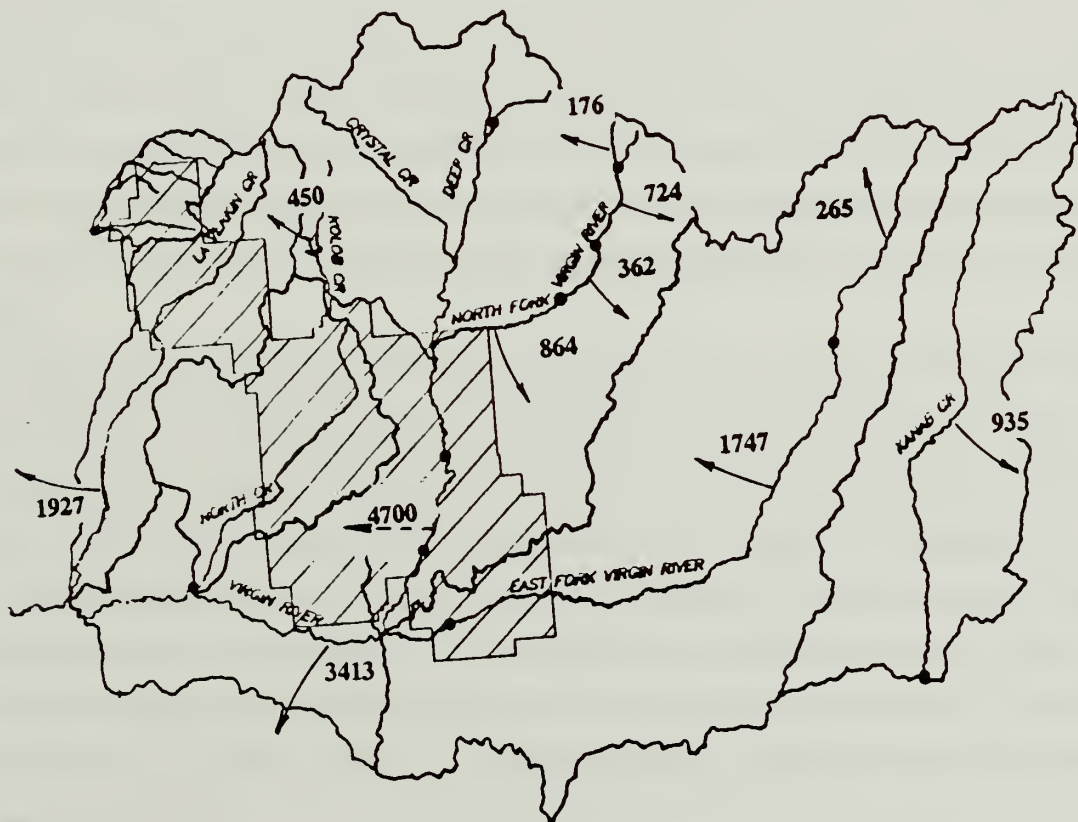


Fig.6 Main Water Depletions in the Zion Region



Notice in Figure 6 the large amount of water diverted from the NFVR through the Springdale Canal, a short distance upstream from the USGS gage at site (12). USGS flows record at site (12) includes flows diverted using the Springdale Canal (until water-year 1988), although that mass of water actually does not reach the gaging station.

The estimated water depletions in the Virgin River basin should be added to the measured flows to develop estimated "natural" conditions. Table 1 includes mean annual discharge values (in cfs/year and ac-ft) for existing and natural conditions. The last column in Table 1 lists percentage reduction in natural flow due to water consumptive use. These percentages were computed as average for the period of flow record. Consequently, estimates of natural flows and percent of change for stations with short period of record are less reliable than the estimates at sites with long records. This has been demonstrated in a previous study (Diaz, 1993 - Section 4), revealing that the long-term mean annual flow for the NFVR at site (9) should be significantly less than the value computed from the available six years of flow record. Based on findings from the cited report, the percent reduction in natural flow at Site (9) should increase from 6.4% (as indicated in Table 1) to 10.3%, after adjusting the corresponding mean annual discharge. It is reasonable to expect changes in the percentages listed in Table 1 for those stations located at high elevations having short periods of record.

The monthly disaggregation of water depletions shown in Figure 7 indicates that most of the consumptive use takes place during the summer months. Water depletions peaks approximately at the same time that the mean-annual hydrograph starts to decay. The largest depletions taking occur during the low-flow months of July, August and September.

Water depletions curves shown in Figure 7 correspond to average conditions at three hydrological subareas: the East Fork of the Virgin River, the North Fork of the Virgin River and the Virgin River. Monthly estimates were obtained from the State of Utah (1983). The fourth curve, Springdale Canal, was computed based on 20 years of diversion records provided by the USGS.

To illustrate the extent natural flow conditions are being affected by surface water diversions in the Virgin River tributaries, a simple computation is included. The analysis is performed for monthly time intervals and from the water quantity point of view. The reach



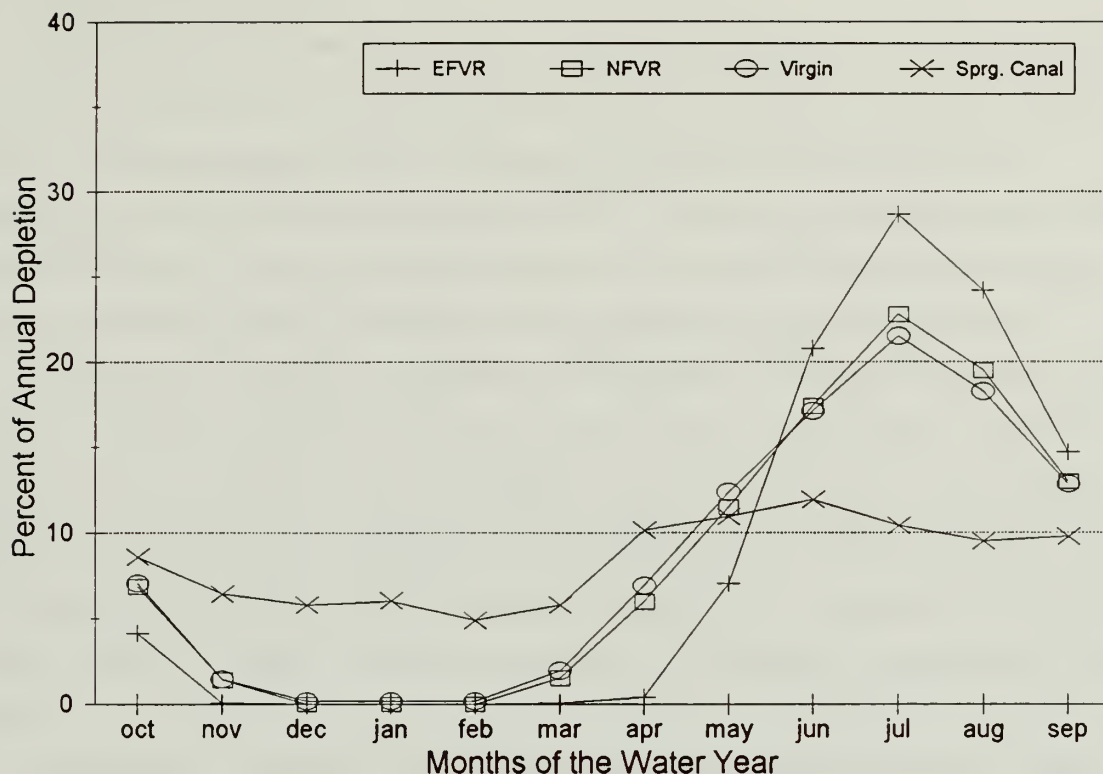


Fig.7 Monthly Distribution of Water Depletions

of the NFVR immediately downstream from site (9) is selected for the analysis. Depletions values obtained from Figure 6 indicate an average of 1,262 ac-ft of water are removed from the river up to Site (9) every year. Moreover, Figure 7 shows July (the most critical month) as the month with the largest depletion, with 22.8% of the annual value. Consequently, the average depletion during the month of July up to site (9) amounts to 290 Ac-Ft, equivalent to a continuous flow of 4.8 cfs. The long-term mean-annual hydrograph at site (9), included as Figure 6 in a previous report (Diaz, 1993), shows July with an average flow of 11 cfs. The estimated depletion for July is added to the existing flow to yield a total flow of 15.8 cfs. These figures indicate that 30% of the presumed natural flows are being diverted from the NFVR upstream from site (9) during the month of July. This finding emphasize the importance of considering water depletions not only at the annual level, as presented in Table 1, but also during shorter time periods.



### 5.3 Precipitation Records

The location of the weather stations and their precipitation records were obtained from the Climatological Data Summary published by the National Climatic Data Center (NCDC). Technical support for the verification and gathering of the most recent precipitation records was provided by Balling (1993). Eighteen (18) weather stations were chosen for the study. They were selected based on the length of their records and their proximity to the study area. The location of the stations are displayed in Figure 8.

According to the NCDC categorization, eleven stations belong to the South-Central Division, five stations to the Dixie Division and two stations to the Western Division. The eighteen stations encompass a large geographical area, surrounding Zion, and extending beyond the boundaries of the Upper Basin of the Virgin River. Station information such as station name and ID number, division, latitude, longitude, elevation and period of record are provided in Table 3. Figure 9 displays a bar graph with the periods of precipitation records available.

Almost half of the stations listed in table 9 have long records that started around 1930. Most of the remaining stations started collecting data between the late 1940's and the early 1950's. Fortunately, the majority of the stations surrounding Zion are ones with long records. The stations are: Alton, Orderville, Kanab, Zion NP, New Harmony and Cedar City FAA Airport. The only exception is Blowhard Mountain Radar station, located at the north boundary of the NFVR basin, which has a short and discontinued record. The percentage of missing years of record varies from station to station, with an average value of 7.7% among the stations. The stations with the largest number of missing-years are located the farthest from the Park, with the exception of Blowhard Mountain Radar station. Precipitation data for the study consist of annual precipitation (in inches). Table 4 shows the annual precipitation values on record, year by year, for all the stations. Actually, monthly values of precipitation instead of annual values were downloaded from the NCDC database. Monthly values were then rearranged from the calendar year to the water year format and the annual totals recomputed, from October to September.



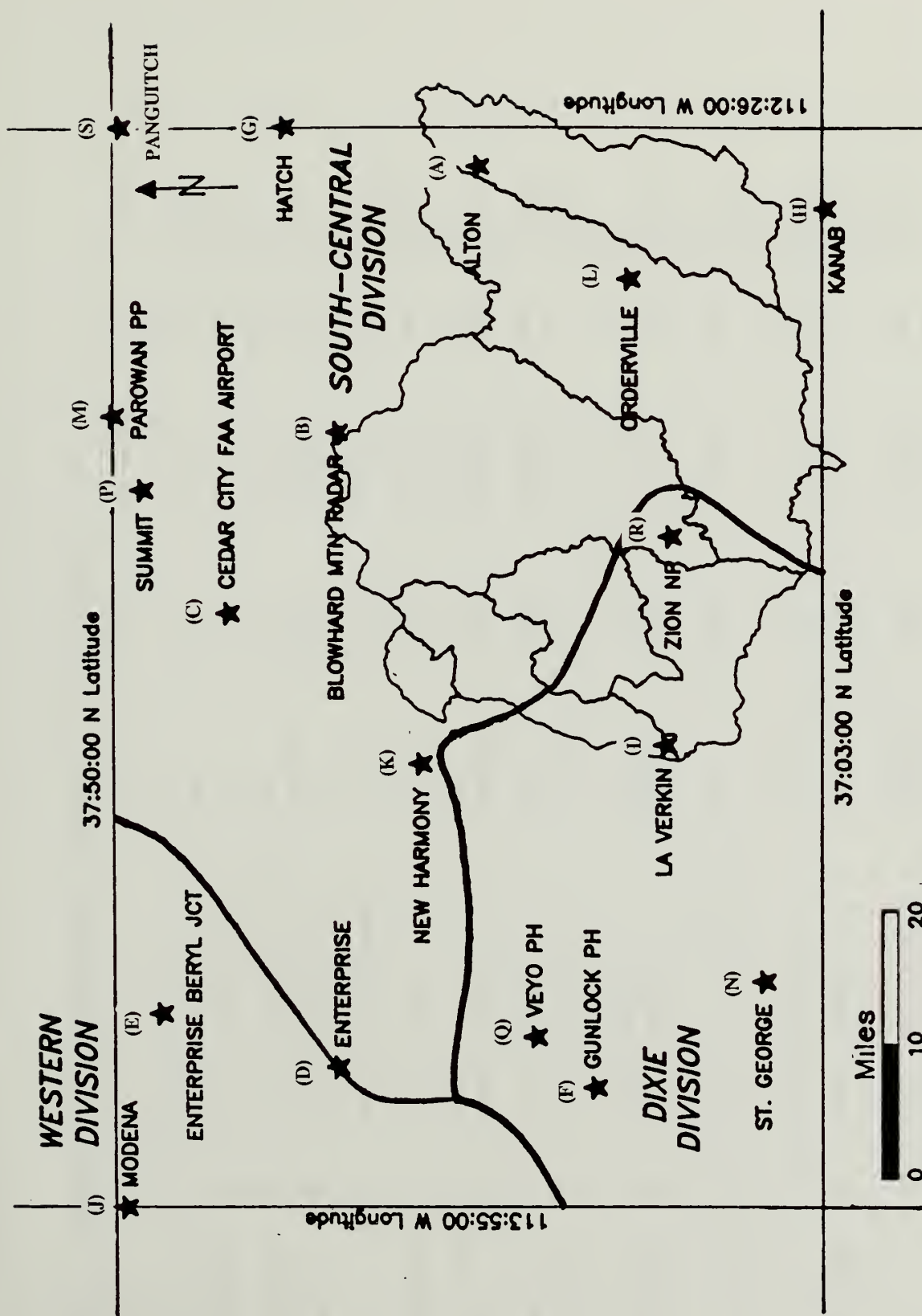


Fig.8 Location of Selected Precipitation Stations



Table 3. Precipitation Gaging Stations Used in the Study, Basic Information

Division	Site	Station ID	Station Name	County	Latitude	Longitude	Elev. [ft]	Period of Record 19__	No. Yrs
South-Central	(A)	0086	Alton	Kane	N37:26	W112:29	7040	29-83,85-92	63
South-Central	(B)	0757	Blowhard Mtn Radar	Iron	N37:35	W112:51	10696	65-71,73-83, 86-90,92	24
South-Central	(C)	1267	Cedar City Faa Airport	Iron	N37:42	W113:06	5610	32-92	61
South-Central	(D)	2558	Enterprise	Washington	N37:34	W113:43	5320	55-81,83-92	37
Western	(E)	2561	Enterprise Beryl Jet	Iron	N37:46	W113:39	5150	41-48,51, 61-90,92	40
Dixie	(F)	3506	Gunlock Powerhouse	Washington	N37:17	W113:44	4110	32-67,69 72-87,89-90,92	56
South-Central	(G)	3776	Hatch	Garfield	N37:39	W112:26	6908	39-62,65-68, 70,75-92	47
South-Central	(H)	4508	Kanab	Kane	N37:03	W112:32	4950	32-92	61
Dixie	(I)	4968	La Verkin	Washington	N37:12	W113:16	3220	51-62,66-69, 71-92	38
Western	(J)	5752	Modena	Iron	N37:48	W113:55	5459	32-76,83-92	55
South-Central	(K)	6181	New Harmony	Washington	N37:29	W113:18	5280	41-43,45-61, 63-67,69-76, 78-89	45
South-Central	(L)	6534	Orderville	Kane	N37:16	W112:38	5460	29-92	64
South-Central	(S)	6601	Panguitch	Garfield	N37:49	W112:26	6610	32-46,48,51-55, 59-62,65-72, 74-92	52
South-Central	(M)	6686	Parowan Power Plant	Iron	N37:50	W112:50	6000	32-36,38-43, 47-54,56-73, 75-92	55
Dixie	(N)	7516	St. George	Washington	N37:07	W113:34	2760	29-63,67, 69-77,79-91	58
South-Central	(P)	8456	Summit	Iron	N37:48	W112:56	6000	53-58,61-63, 65-67,73, 75-81,83-92	30
Dixie	(Q)	9136	Veyo Powerhouse	Washington	N37:21	W113:40	4600	58-67,70-92	33
Dixie	(R)	9717	Zion National Park	Washington	N37:13	W112:59	4050	29-92	64



Station ID	Station No.	Station Name	1920	1930	1940	1950	1960	1970	1980	1990
0086	A)	Alton	—	—	—	—	—	—	—	—
0757	B)	Blowhard Mtn Radar						—	—	—
1267	C)	Cedar City Faa Airport		—				—	—	—
2558	D)	Enterprise				—	—	—	—	—
2561	E)	Enterprise Beryl Jct			—	—	—	—	—	—
3506	F)	Gunlock Powerhouse		—		—	—	—	—	—
3776	G)	Hatch		—		—	—	—	—	—
4508	H)	Kanab		—		—	—	—	—	—
4968	I)	La Verkin				—	—	—	—	—
5752	J)	Modena		—		—	—	—	—	—
6181	K)	New Harmony			—	—	—	—	—	—
6534	L)	Orderville		—		—	—	—	—	—
6686	M)	Parowan Power Plant		—		—	—	—	—	—
7516	N)	St. George		—		—	—	—	—	—
8456	P)	Summit				—	—	—	—	—
9136	Q)	Veyo Powerhouse					—	—	—	—
9717	R)	Zion National Park		—		—	—	—	—	—
6601	S)	Panguitch		—	—	—	—	—	—	—

Fig.9 Period of Records of Precipitation Gaging Stations



Table 4. Annual Precipitation (in inches) at Selected Stations

Year	Precipitation Gaging Stations at Sites ....																	
	(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)	(I)	(J)	(K)	(L)	(M)	(N)	(P)	(Q)	(R)	(S)
	Alton	Blowhard	Cedar City	Enterprise	Entpr Bry J	Gunlock	Hatch	Kanab	La Verkin	Modena	New Harm	Orderville	Parowan	St. George	Summit	Veyo Phw	Zion NP	Panguitch
1929	18.19											12.83		7.53			13.70	
1930	13.25											13.49		7.75			11.89	
1931	11.62											10.47		8.55			6.73	
1932	22.68		16.48			17.52		17.38		11.62		21.40	13.96	15.77			22.61	10.42
1933	10.78		9.63			8.07		9.19		8.34		9.81	7.51	5.13			9.21	7.98
1934	15.13		7.88			6.55		10.77		6.74		8.64	7.45	6.27			9.64	7.86
1935	15.27		10.51			12.06		12.94		10.45		16.13	10.48	9.99			17.14	8.17
1936	15.11		11.88			12.31		8.94		8.27		13.34	10.33	7.39			12.22	7.85
1937	22.82		13.43			14.86		18.60		13.14		23.65		10.13			18.12	10.62
1938	17.00		13.06			11.13		13.11		13.52		13.03	11.92	7.11			13.46	12.2
1939	16.81		11.98			11.93	12.47	15.42		10.57		17.39	12.51	9.99			16.45	12.84
1940	12.45		8.73			10.82	8.18	14.37		7.68		17.66	10.81	8.06			15.65	9.66
1941	20.42		14.22		14.47	20.06	13.35	20.36		12.72	23.81	21.45	16.30	13.48			22.63	11.61
1942	14.19		13.02		12.42	11.15	10.66	11.95		11.51	17.83	14.08	13.31	8.75			14.03	8.69
1943	15.27		12.04		9.90	13.61	8.13	13.82		12.73	14.72	15.50	10.67	10.38			17.27	8.16
1944	13.15		10.43		6.65	12.05	9.35	10.82		8.34		13.13		6.43			16.63	9.16
1945	15.56		10.15		10.50	12.18	10.37	10.56		11.66	17.24	11.04		7.60			13.34	4.88
1946	15.50		10.26		8.72	10.76	10.70	10.05		8.33	11.43	12.05		5.22			11.62	8.93
1947	16.93		13.45		12.58	14.83	11.08	12.54		14.44	23.31	14.41	15.27	8.69			15.76	
1948	14.18		11.75		7.93	8.32	8.20	10.98		9.29	13.24	14.42	12.80	6.44			12.12	11.22
1949	19.15		10.72		11.94	12.19	13.92			14.44	18.11	17.31	14.57	8.29			15.47	
1950	13.92		7.59			8.41	7.85	11.06		6.96	15.65	13.07	10.13	6.15			13.89	
1951	15.53		6.98		7.20	9.88	9.53	10.05	9.33	6.62	14.35	10.66	9.69	8.32			11.01	6.90
1952	22.42		10.13			13.52	13.41	15.99	11.51	9.78	23.32	17.19	15.70	8.98			19.30	11.30
1953	8.13		8.48			6.91	8.10	8.65	7.00	4.91	9.52	9.43	10.03	4.92	8.25		10.77	6.49
1954	15.16		10.24			13.42	10.63	13.45	12.79	8.81	16.84	15.37	12.32	8.52	12.23		16.45	8.70
1955	14.40		8.50	12.05		13.50	8.24	9.31	6.98	10.38	15.59	12.21		6.45	8.31		10.25	7.63
1956	8.11		6.83	7.45		4.48	5.41	7.66	5.91	4.30	10.68	9.03	8.68	4.32	7.12		8.52	
1957	16.73		9.83	11.65		10.32	9.52	12.38	9.01	7.14	14.11	17.27	12.95	7.11	10.95		13.84	
1958	26.39		10.64	16.83		20.25	15.39	19.00	17.49	13.38	21.54	23.12	14.22	13.80	13.46	21.36	22.83	
1959	11.76		4.90	8.23		7.89	11.28	6.95	7.44	5.45	11.70	8.94	7.66	4.89		9.45	7.92	6.05
1960	13.34		5.63	9.20		10.51	6.98	10.68	9.71	6.94	10.82	12.40	5.40	6.97		10.03	12.83	6.25
1961	16.41		15.26	14.41	11.18	8.50	15.17	10.23	9.52	9.73	17.27	13.91	13.99	7.32	16.60	11.75	16.42	14.35
1962	16.36		8.66	14.72	9.33	10.29	7.36	10.46	8.75	5.30		16.50	12.83	4.83	12.20	12.25	13.75	9.12
1963	15.24		11.44	10.85	8.58	8.52		11.08		8.17	13.78	13.21	14.19	7.43	11.64	9.48	13.83	
1964	14.02		8.40	10.68	10.08	7.20		10.58		7.30	12.44	11.08	10.53			8.00	10.32	
1965	19.74	35.82	12.97	12.35	9.19	11.05	10.63	12.61		10.60	17.88	14.32	17.07		14.04	10.96	13.69	13.23
1966	17.75	30.06	7.98	11.60	7.39	11.39	9.05	12.98	10.47	7.35	18.53	14.90	10.42		10.04	11.63	14.82	9.41
1967	24.09	42.59	17.06	18.83	11.09	12.35	18.00	19.91	12.00	11.98	24.44	22.97	17.34	7.89	14.81	16.93	19.31	16.46
1968	17.92	29.15	10.41	12.22	12.34		8.88	11.64	8.91	8.71		14.37	12.41				14.14	11.22
1969	26.23	34.93	11.51	19.91	10.19	16.03		19.97	13.34	15.57	26.12	21.02	12.26	9.66			15.63	11.41
1970	11.96	28.18	10.64	12.91	19.19		9.51	9.93		11.77	13.61	11.54	13.62	7.12		10.05	12.17	9.61
1971	13.42	28.04	9.32	10.64	6.72			9.22	9.91	9.02	15.35	13.42	13.72	6.06		13.25	12.33	9.62
1972	15.98		9.77	12.44	7.97	7.66		7.67	11.29	7.57	14.51	12.54	11.84	6.50		8.67	14.40	11.86
1973	22.28	39.15	14.59	19.70	15.47	17.23		16.69	16.28	11.55	30.37	16.98	23.33	11.35	17.45	19.76	21.88	
1974	10.14	19.58	8.02	9.85	7.29	9.50		6.31	6.80	5.15	10.31	7.29		4.51		9.30	8.09	5.50
1975	16.94	31.53	13.71	14.52	9.49	13.80	12.27	17.15	11.60	12.61	15.30	13.87	10.78	9.37	12.13	12.70	16.38	9.29
1976	13.28	22.73	6.92	11.00	8.34	9.21	9.43	10.43	7.55	7.99	15.47	9.47	7.64	5.28	7.45	10.66	8.91	7.65
1977	9.92	19.61	7.69	8.79	9.88	9.52	8.68	5.50	6.13			8.73	6.65	9.47	8.98	12.93	10.92	6.78
1978	16.81	29.34	10.75	21.52	14.07	18.43	10.51	18.16	15.95		27.57	20.86	10.00		12.32	19.56	22.41	9.06
1979	22.32	42.09	12.76	19.77	11.13	15.79	15.10	19.37	15.56		25.43	19.25	10.51	12.59	12.34	17.31	18.55	12.28
1980	23.93	36.17	16.19	23.59	12.09	19.75	16.71	22.29	18.52		26.63	23.94	14.19	11.89	16.66	20.46	24.24	11.22
1981	11.71	30.50	11.76	15.77	11.01	10.83	12.75	13.77	11.02		16.42	14.70	13.55	9.44	13.47	11.09	15.95	10.96
1982	18.13	36.28	13.98		12.57	12.86	16.47	15.56	12.69		18.51	17.97	10.75	7.70		15.28	16.25	10.14
1983	24.02	40.11	14.50	19.56	11.01	22.97	16.48	21.86	18.56	10.27	28.67	25.19	15.12	14.56	14.35	23.56	25.78	11.67
1984			15.57	12.20	10.82	10.29	12.26	12.74	9.72	12.92	13.15	13.77	18.01	5.48	17.60	13.17	17.72	13.02
1985	17.56		10.74	10.73	10.58	8.85	14.17	13.15	10.50	9.92	18.89	19.06	15.90	8.96	12.72	11.11	14.35	9.05
1986	22.01	29.63	13.88	17.02	11.64	12.73	11.00	16.65	12.00	13.87	17.93	17.50	13.88	7.44	12.69	16.00	17.67	10.39
1987	13.57	26.15	9.71	10.29	8.25	9.74	10.70	14.54	10.52	9.33	14.16	15.99	10.83	7.43	12.15	12.04	12.89	11.98
1988	19.61	33.56	15.32	15.04	12.72		13.48	14.66	15.47	16.48	22.20	20.87	17.56	11.42	15.59	18.11	18.73	12.00
1989	12.01	20.14	8.01	8.93	7.75	7.50	7.78	8.03	8.14	8.28	10.25	9.66	9.67	6.01	11.42	7.69	10.91	6.92
1990	13.30	23.98	8.66	13.96	7.80	13.20	9.71	7.76	8.83	9.76		12.00	10.08	4.78	10.39	12.93	10.81	7.46
1991	12.38		9.06	14.01			10.60	11.57	7.47	7.24		12.43	11.69	4.29	9.16	15.00	12.60	7.44
1992	19.89	25.91	13.55	19.91	14.03	19.65	13.04	19.31	16.51	13								



## 6.0 TRANSFER OF PRECIPITATION INFORMATION

### 6.1 Statement of the Problem

As indicated in Section 3, the computation of annual runoff to annual precipitation ratio at any site requires concurrent precipitation data, available at all gaging sites within the study region, and surface runoff data, measured at the site where the  $k$  coefficient is estimated. Runoff and precipitation records indicate that precipitation measurements have been collected for longer time periods than surface runoff. The reader can contrast the extent of the existing records comparing Figure 5 from a previous report (Diaz, 1992) and Figure 9 from this report. Furthermore, annual precipitation is typically less variable than annual runoff in the arid and semi-arid mountainous regions of the South-West. Due to these two factors, it was decided to complete and extend the precipitation records (instead of the flow records) within the study area. The extended precipitation records will then be used in conjunction with surface runoff data to estimate the runoff coefficients  $k$ .

Runoff records begin at different years and some last for a short number of years. Typically, gaging stations located at low elevations have the longest records, whereas gages for small watersheds at the headwaters have records for only a few years. High altitude stations in the NFVR basin have been in operation for less than 10 years to assess the subbasins water yield. Most of the flow gaging stations in the study area have records starting in the 1970's and late 1960's. Only two stations, sites (15) and (12), started collecting data as early as 1910 and 1926 respectively. On the other hand, 10 out of the 18 weather stations started collecting precipitation data around 1930. The final decision was to adopt 1932 as the earliest year for extending the precipitation records. Consequently, flow records prior to 1932 will be disregarded for the purpose of this study. The percentage of missing values at the 18 stations during the 61 years of record, from 1932 to 1992, see Table 4, amounts to 20.7%. Thus, one-fifth of the complete database needs to be filled-in by using a regression technique. Note that 74% of the missing values are between 1932 to 1960. The remaining 26% occurred during the 1961-1992 period.



## 6.2 Linear Regression Technique

The transfer of information technique presented in this section is used for filling-in missing precipitation observations and extending records beyond their observation periods. The selected technique is linear regression, which implies that the dependent variable and the independent variable/s are linearly associated. The linear relationship allow one variable to be predicted from the other. By definition, multiple linear regression is applied for transferring information to a given site with a short or discontinued record when there are two or more nearby sites with longer records. When information from a single station is used to extend the record at the site of interest, the regression procedure reduces from the multiple to the simple linear regression case. In general, the short record of length  $N_1$  is represented by  $y$  and the longer  $p$  records of length  $(N_1+N_2)$  are represented by the vector  $x$ . The problem is to transfer information from the  $p$  stations with records of length  $(N_1+N_2)$  to the station with short record  $y$ , and at the same time, to improve the estimates of its parameters, the mean and variance. The short record  $y$  of length  $N_1$  may be related to the  $p$  records  $x_t$  by the regression model (Gilroy, 1970),

$$y_t = a + \sum_{i=1}^p b_i x_t^{(i)} + (1-R^2)^{1/2} \alpha \theta \sigma_y \epsilon_t \quad (2)$$

where  $a$  and  $b_i$  ( $i=1, \dots, p$ ) are the parameters of the model.  $R$  is the population multiple correlation coefficient.  $\alpha$  is introduced to remove the bias when the variance  $\sigma_y^2$  is estimated.  $\epsilon_t$  is a normal variable with zero mean and unit variance.  $\theta$  is the indicator parameter equals to 1 when the noise term is added and 0 otherwise. The sample estimates of  $\hat{a}$  and  $\hat{b}$  are given by,

$$\hat{a} = \bar{y}_1 - \sum_{i=1}^p \hat{b}_i \bar{x}_1^{(i)} \quad (3)$$

$$\hat{b}_i = \sum_{j=1}^p d_1^{(ij)} c_1^{(j)} \quad i=1, \dots, p \quad (4)$$



with  $d_1^{(ij)}$  the elements of the inverse of the matrix whose elements are:

$$g_1^{(ij)} = \sum_{t=1}^{N_1} [x_t^{(i)} - \bar{x}_1^{(i)}] [x_t^{(j)} - \bar{x}_1^{(j)}] , \quad i, j = 1, \dots, p \quad (5)$$

$$c_1^{(j)} = \sum_{t=1}^{N_1} [x_t^{(j)} - \bar{x}_1^{(j)}] [y_t - \bar{y}_1] , \quad j = 1, \dots, p \quad (6)$$

representing the cross-covariance between the series. The mean of the independent series,  $\bar{x}_1^{(i)}$ , and the mean and variance of the dependent series,  $\bar{y}_1$  and  $s_1(y)$ , are given respectively by,

$$\bar{x}_1^{(i)} = \frac{1}{N_1} \sum_{t=1}^{N_1} x_t^{(i)} , \quad i = 1, \dots, p \quad (7)$$

$$\bar{y}_1 = \frac{1}{N_1} \sum_{t=1}^{N_1} y_t \quad (8)$$

$$s_1(y) = \left[ \frac{1}{N_1 - 1} \sum_{t=1}^{N_1} (y_t - \bar{y}_1)^2 \right]^{1/2} \quad (9)$$

The multiple correlation coefficient  $R$  is estimated from the concurrent  $N_1$  observations as (Yevjevich, 1972),

$$\hat{R} = \left[ \frac{\sum_{i=1}^p \hat{\beta}_i c_1^i}{\sum_{t=1}^{N_1} (y_t - \bar{y}_1)^2} \right]^{1/2} \quad (10)$$



Equation (2) is used to extend the  $y$  values, so as to yield the sequence,

$$y_1, y_2, \dots, y_{N_1}, \hat{y}_{N_1+1}, \dots, \hat{y}_{N_1+N_2} \quad (11)$$

where  $\hat{y}_t$  represents the sequence estimated from Eq.(2). A basic underlying assumption made when using simple or multiple linear regression models such as Eq.(2) is that the variables involved are bivariate or multivariate normal respectively. Annual values of precipitation are assumed approximately normal, therefore no transformation of the original data will be made.

### 6.3 Regression Results

The transfer of information was carried out by a "successive extension" procedure, whereby the precipitation record at one or more gaging sites are used as independent variables in extending the short precipitation record at a station which in turn is used to extend the record of another station and thus successively. This approach is necessary when dealing with gaging stations having different record lengths and intermediate missing values. Actual precipitation measurements were used for data transfer when possible rather than previously regressed values.

Simple regressions and multiple regression combinations were attempted to detect the best possible set of stations to be used for fill-in missing data at a given site. When several gaging stations could be used to transfer data to a site with a short record, the selection of the stations was dependent on various factors such as: distance among stations, longitude of records, concurrent information, and a statistical test based on the simple or multiple correlation coefficient, the  $R^2$  index, derived from Eq.(10).

$R^2$  should be interpreted as the proportion of total variability in  $y_t$  as explained by  $x_t$  or  $x_t^{(1)}, \dots, x_t^{(p)}$ , for the cases of simple and multiple regression models respectively. High values of  $R^2$  indicate a strong linear relationship between the variable with missing data  $y_t$  and other station/s. The correlation among stations with the highest value of  $R^2$  was selected for filling-in the missing data, provided that concurrent values of







Table 5. Parameters of the Regression Equations (Continuation)

<b>B = f (A,C )</b>			<b>K = f (D)</b>			and	<b>K = f (R)</b>		
Regression Output:			Regression Output:				Regression Output:		
Constant	6.977847		Constant	0.456937			Constant	1.730302	
Std Err of Y Est	3.513003		Std Err of Y Est	2.50332			Std Err of Y Est	3.025821	
R Squared	0.76		R Squared	0.83			R Squared	0.70	
No. of Observations	24		No. of Observations	31			No. of Observations	45	
Degrees of Freedom	21		Degrees of Freedom	29			Degrees of Freedom	43	
X Coefficient(s)	0.686746	0.995589	X Coefficient(s)	1.250128			X Coefficient(s)	1.040464	
Std Err of Coef.	0.232005	0.387424	Std Err of Coef.	0.106057			Std Err of Coef.	0.104348	
<b>E = f (J,C)</b>			<b>G = f (A,C)</b>			and	<b>G = f (A,B)</b>		
Regression Output:			Regression Output:				Regression Output:		
Constant	3.817624		Constant	1.04542			Constant	0.066771	
Std Err of Y Est	2.166546		Std Err of Y Est	1.69211			Std Err of Y Est	1.782074	
R Squared	0.37		R Squared	0.67			R Squared	0.71	
No. of Observations	40		No. of Observations	47			No. of Observations	20	
Degrees of Freedom	37		Degrees of Freedom	44			Degrees of Freedom	17	
X Coefficient(s)	0.404262	0.207741	X Coefficient(s)	0.32474	0.43480		X Coefficient(s)	0.111592	0.325834
Std Err of Coef.	0.173168	0.183007	Std Err of Coef.	0.07680	0.11054		Std Err of Coef.	0.155984	0.105375
<b>I = f (R)</b>			<b>P = f (C,M)</b>						
Regression Output:			Regression Output:						
Constant	0.40785		Constant	2.12577					
Std Err of Y Est	1.35247		Std Err of Y Est	1.210247					
R Squared	0.86		R Squared	0.83					
No. of Observations	35		No. of Observations	30					
Degrees of Freedom	33		Degrees of Freedom	27					
X Coefficient(s)	0.69774		X Coefficient(s)	0.538453	0.313535				
Std Err of Coef.	0.04985		Std Err of Coef.	0.112937	0.094668				
<b>Q = f (F)</b>			<b>S = f (M)</b>						
Regression Output:			Regression Output:						
Constant	1.64274		Constant	2.941832					
Std Err of Y Est	1.279913		Std Err of Y Est	1.585097					
R Squared	0.92		R Squared	0.55					
No. of Observations	33		No. of Observations	46					
Degrees of Freedom	31		Degrees of Freedom	44					
X Coefficient(s)	0.977419		X Coefficient(s)	0.58118					
Std Err of Coef.	0.053482		Std Err of Coef.	0.07912					

As expected, the largest degree of association for any given precipitation recording site is provided by its nearby station for the case of bivariate regression, or group of adjacent stations for the multiple regression case. Generally, the highest  $R^2$  values are obtained for



stations aligned in the north-west to south-east direction (downwind direction), coinciding with the northwesterly path of the storms. Appendix I contains sketches showing the most significant correlations attempted. The letter inside dark circles identifies the station with missing data. Similarly, light circles represent the surrounding stations used for transferring the information. Numbers attached to lines connecting pair of stations denote values. When more than two circles are connected, a multiple association of stations is implied.

Results from the regression analysis were in general very satisfactory. The only exception being the station at Site (E), Enterprise, which shows a poor correlation with the precipitation records at the neighboring stations. Fortunately, Enterprise is located far away from the Park boundaries, minimizing the adverse effect of the poor interstation correlation. Some pair of stations with the highest  $R^2$  values could not be used because the lack of concurrent information to perform the regression analysis. In those cases, the next best pair of stations were selected. Figure 10 shows an example of a multiple-regression line between annual precipitation values recorded at Site (P) versus Sites (C) and (M).

#### 6.4 Improvement of Estimates

When using correlation analysis to extend precipitation records a question arises as whether the addition of the  $N_2$  values in Eq.(11) improves the estimates of the parameters of  $y$ . The criterion used to indicate whether the estimated mean and variance of the time series are improved or not by the record extension is based on comparing their variances. In general, two estimates of a parameter  $\gamma$  are computed and compared. One estimated from the recorded data of  $N_1$  years only, denoted by  $Var[\gamma_1]$ , and the other estimated by the extended record of  $(N_1+N_2)$  years via the regression model of Eq.(2), and denoted by  $Var[\gamma]$ . Gilroy (1970) provides the theoretical expressions to compute the new estimates of the mean  $\bar{y}$  and of the variance  $S^2(y)$  of the extended sequences, as well as their corresponding variances,  $Var[\bar{y}]$  and  $Var[S^2(y)]$ . The interested reader can find the equations and their derivations in the cited reference. This report presents only the final conditions to be met.



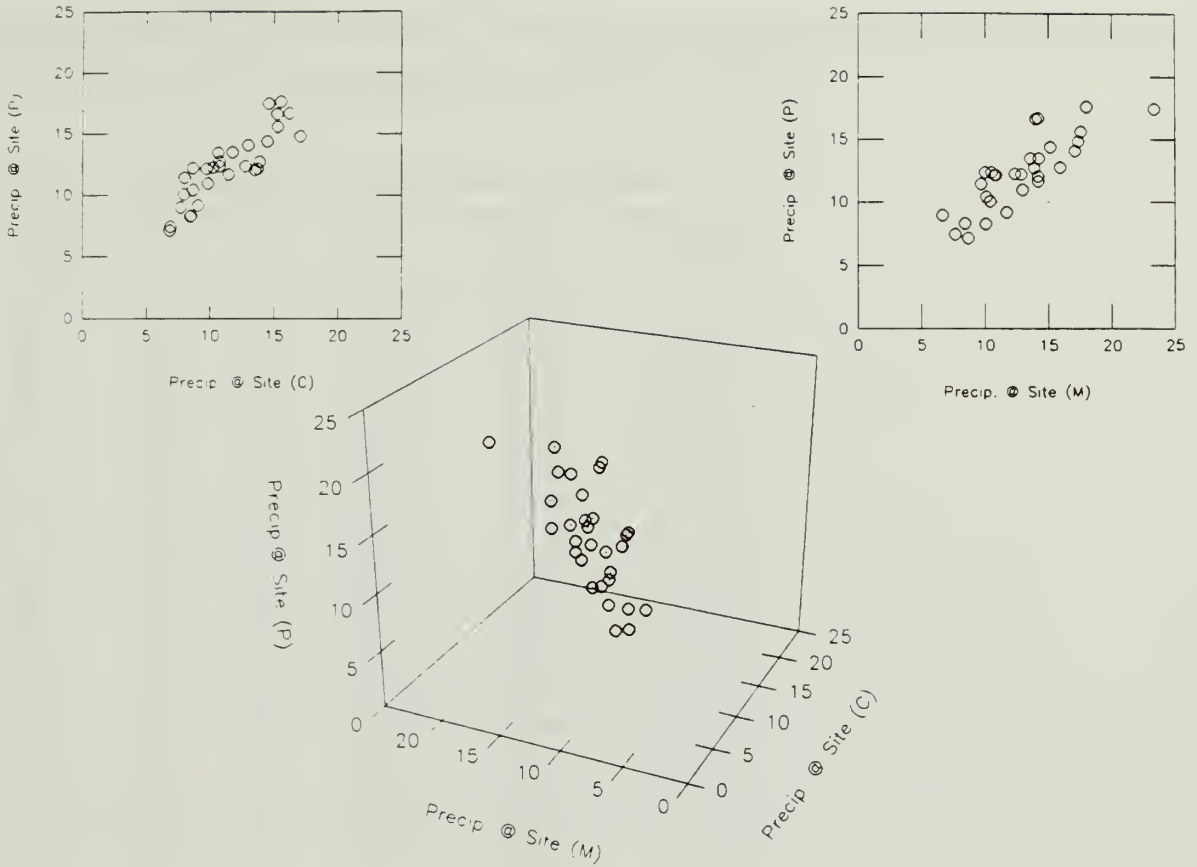


Fig.10 Multiple-Regression of Annual Precipitation at Site (P) Versus Sites (C) and (M).

Improvement of the Estimate of the Mean : By definition, the transfer of information from the " $p$ " nearby sites increases or improves the precision of the estimate of the mean if the variance of the mean estimator based on the extended/completed data,  $Var[\bar{y}]$ , is smaller than the variance of the mean estimator of the original record of length  $N_1$ ,  $Var[y_1]$ . This condition will hold if (Gilroy, 1970),

$$Var[\bar{y}] < Var[\bar{y}_1] \quad \text{if} \dots R > R_c = \sqrt{\frac{p}{N_1 - 2}} \quad (12)$$

where  $R$  denotes the multiple correlation coefficient. The right hand side of Eq.(12) is called the critical minimum correlation coefficient  $R_c$  for improving the estimate of the mean. For the simple linear regression case, Eq.(12) is still applicable by making  $p=1$ . Results of



the computations for all the stations that required data extension are presented in Table 6. There is shown that the condition  $R > R_c$  holds in all cases, implying that the correlation was useful for improving estimates of the mean for all series.

Table 6. Improvement of the Estimate of the Mean

Station	$N_1$	$p$	$R$	$R_c$	Remarks
(A)	63	1	0.70	0.128	$R > R_c$
(B)	24	2	0.76	0.302	$R > R_c$
(D)	31	1	0.83	0.186	$R > R_c$
(E)	40	2	0.37	0.267	$R > R_c$
(F)	29	1	0.91	0.867	$R > R_c$
	32	1	0.72	0.183	$R > R_c$
(G)	47	2	0.67	0.175	$R > R_c$
	20	2	0.71	0.170	$R > R_c$
(I)	35	1	0.86	0.174	$R > R_c$
(J)	27	2	0.57	0.283	$R > R_c$
(K)	31	1	0.83	0.186	$R > R_c$
	45	1	0.70	0.152	$R > R_c$
(M)	54	1	0.52	0.139	$R > R_c$
	28	1	0.68	0.196	$R > R_c$
(N)	36	1	0.76	0.171	$R > R_c$
	51	1	0.68	0.143	$R > R_c$
(P)	30	2	0.83	0.267	$R > R_c$
(Q)	33	1	0.92	0.180	$R > R_c$
(S)	46	1	0.55	0.151	$R > R_c$

Improvement of the Estimate of the Variance: Similarly, for  $S^2(y)$  (extended record) to be a better estimate of  $\sigma_y^2$  than  $S_1^2(y)$  (short record), the following inequalities should be satisfied (Gilroy, 1970),

$$Var[S^2(y)] < Var[S_1^2(y)] \quad \text{if} \dots \quad R > R_c = \left[ \frac{-B + \sqrt{B^2 - 4AC}}{2A} \right] \quad (13)$$

where  $R$  again denotes the multiple correlation coefficient. The value of the right side of Eq.(13) is called the critical minimum multiple correlation coefficient  $R_c$  required to improve the estimate of the variance.  $A$ ,  $B$  and  $C$  are functions of  $N_1$ ,  $N_2$ ,  $\theta$  and  $p$ , obtained from the above reference. Results from the computation of Eq.(13) are summarized in Table 7.



Table 7. Improvement of the Estimate of the Variance

Station	$N_1$	$N_2$	$p$	$\theta$	$R$	$R_c$	Remarks
(A)	63	1	1	0	0.70	0.60	$R > R_c$
(B)	24	37	2	0	0.76	0.82	$R < R_c$
(D)	31	24	1	0	0.83	0.83	$R > R_c$
(E)	40	21	2	0	0.37	0.80	$R < R_c$
(F)	29	4	1	0	0.91	0.63	$R > R_c$
	32	1	1	0	0.72	0.63	$R > R_c$
(G)	47	10	2	0	0.67	0.72	$R < R_c$
	20	5	2	0	0.71	0.49	$R > R_c$
(I)	35	23	1	0	0.86	0.84	$R > R_c$
(J)	27	6	2	0	0.57	0.53	$R > R_c$
(K)	31	6	1	0	0.83	0.67	$R > R_c$
	45	10	1	0	0.70	0.77	$R < R_c$
(M)	54	5	1	0	0.52	0.65	$R < R_c$
	28	1	1	0	0.68	0.63	$R > R_c$
(N)	36	4	1	0	0.76	0.65	$R > R_c$
	51	2	1	0	0.68	0.63	$R > R_c$
(P)	30	31	2	0	0.83	0.82	$R > R_c$
(Q)	33	28	1	0	0.92	0.85	$R > R_c$
(S)	46	9	1	0	0.55	0.77	$R < R_c$

By adopting  $\theta = 0$  in Eq.(2), high values of  $R_c$  are originated by the right-side of Eq.(13), see Table 7, compared with the case for  $\theta = 1$ . That, in turn, makes more difficult the satisfaction of the inequality in Eq.(13). It is suspected that the inclusion into the extended portion of the record of extreme hydrological years modifies significantly the distribution of the annual values at some stations.

Relative Information Index : the concept of relative information is also used for measuring the precision of an estimated parameter after extending or completing the short or missing record by linear regression. The relative information index "I" is the ratio of the variance of the parameter estimated from the original record of length  $N_1$  values, to the variance estimated from the combined record of  $(N_1 + N_2)$  values, that is,

$$I = \text{Var}[\hat{\gamma}_1] / \text{Var}[\hat{\gamma}] \quad (14)$$



The transfer of information improves the precision of the estimate of a parameter when

$Var[\hat{\gamma}_1] > Var[\hat{\gamma}]$  , that is,  $I > 1$ . Table 8 contains the results of the computations.

Table 8. Relative Information Index

Station	I	Station	I
(A)	1.02	(J)	0.88
(B)	1.47	(K)	1.13
(D)	1.29	(M)	1.07
(E)	1.24	(N)	1.02
(F)	1.05	(P)	1.32
(G)	1.06	(Q)	1.25
(I)	1.26	(S)	0.98

The variance at station (J) computed from the combined sequence exceeds the one computed from the recorded series of size  $N_1$  alone. Nevertheless, the record at station (J) was completed (only 10% of missing values) to be able to complete our study.

## 6.5 Areal Distribution of Annual Precipitation

Based on the regression procedure outlined above, incomplete records of annual precipitation at all gaging sites within the study area were filled-in and/or extended for the period [1932-1992]. Table 9 shows measured and estimated values of annual precipitation jointly with the latter highlighted. The bottom portion of Table 9 provides some basic statistics corresponding to the extended series that can be compared with the same statistics computed for the measured values displayed in Table 4.

The long-term mean-area distribution of precipitation is portrayed by isohyetal maps, which traditionally are made available by the U.S. Weather Bureau for 30-years interval. However, due to the specific requirements of this study the available maps were not suitable. Isohyetal maps for the Zion region were prepared by interpolating areal rainfall values. This approach, termed the Isohyetal Method (Viessman, 1977), provides an accurate description of "average" precipitation conditions over an area, although storm pattern characteristics may strongly influence the areal variability of precipitation.



Table 9. Extended/Filled-in Annual Precipitation Records (inches/yr)

Year	Precipitation Gaging Stations at Sites.....																		
	(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)	(I)	(J)	(K)	(L)	(M)	(N)	(P)	(Q)	(R)	(S)	
	Alton	Blowhard	Cedar Cr	Enterprise	Enterprise	Gunlock	Hatch	Kanab	La Verdon	Modena	New Har	Orderville	Parowan	St. Georg	Summit	Veyo Phw	Zion NP	Panguitch	
1929	18.19											12.83		7.53			13.70		
1930	13.25											13.49		7.75			11.89		
1931	11.62											10.47		8.55			6.73		
1932	22.68	38.96	16.48	18.80	11.94	17.52	15.58	17.38	16.18	11.62	25.26	21.40	13.96	15.77	15.38	18.77	22.61	10.42	
1933	10.78	23.97	9.63	9.58	9.19	8.07	8.73	9.19	6.83	8.34	11.31	9.81	7.51	5.13	9.67	9.53	9.21	7.98	
1934	15.13	25.21	7.88	9.87	8.18	6.55	9.38	10.77	7.13	6.74	11.76	8.64	7.45	6.27	8.70	8.04	9.64	7.86	
1935	15.27	27.93	10.51	15.04	10.23	12.06	10.57	12.94	12.37	10.45	19.56	16.13	10.48	9.99	11.07	13.43	17.14	8.17	
1936	15.11	29.18	11.88	11.65	9.63	12.31	11.12	8.94	8.93	8.27	14.44	13.34	10.33	7.39	11.76	13.67	12.22	7.85	
1937	22.82	36.02	13.43	15.71	11.92	14.86	14.30	18.60	13.05	13.14	20.58	23.65	14.28	10.13	13.84	16.17	18.12	10.62	
1938	17.00	31.65	13.06	12.50	12.00	11.13	12.24	13.11	9.80	13.52	15.73	13.03	11.92	7.11	12.90	12.52	13.46	12.2	
1939	16.81	30.45	11.98	14.56	10.58	11.93	12.47	15.42	11.89	10.57	18.85	17.39	12.51	9.99	12.50	13.30	16.45	12.84	
1940	12.45	24.22	8.73	14.01	8.74	10.82	8.18	14.37	11.33	7.68	18.01	17.66	10.81	8.06	10.22	12.22	15.65	9.66	
1941	20.42	35.16	14.22	17.85	14.47	20.06	13.35	20.36	16.20	12.72	23.81	21.45	16.30	13.48	14.89	21.25	22.63	11.61	
1942	14.19	29.69	13.02	13.89	12.42	11.15	10.66	11.95	10.20	11.51	17.83	14.08	13.31	8.75	13.31	12.54	14.03	8.69	
1943	15.27	29.45	12.04	11.83	9.90	13.61	8.13	13.82	12.46	12.73	14.72	15.50	10.67	10.38	11.95	14.95	17.27	8.16	
1944	13.15	26.39	10.43	14.69	6.65	12.05	9.35	10.82	12.01	8.34	19.02	13.13	11.86	6.43	11.46	13.42	16.63	9.16	
1945	15.56	27.77	10.15	13.50	10.50	12.18	10.37	10.56	9.72	11.66	17.24	11.04	11.63	7.60	11.24	13.55	13.34	4.88	
1946	15.50	27.84	10.26	9.65	8.72	10.76	10.70	10.05	8.52	8.33	11.43	12.05	11.72	5.22	11.32	12.16	11.62	8.93	
1947	16.93	32.00	13.45	17.52	12.58	14.83	11.08	12.54	11.40	14.44	23.31	14.41	15.27	8.69	14.16	16.14	15.76	11.82	
1948	14.18	28.41	11.75	10.85	7.93	8.32	8.20	10.98	8.86	9.29	13.24	14.42	12.80	6.44	12.47	9.77	12.12	11.22	
1949	19.15	30.80	10.72	14.08	11.88	11.94	12.19	13.92	11.20	14.44	18.11	17.31	14.57	8.29	12.47	13.31	15.47	11.41	
1950	13.22	24.09	7.59	12.45	8.21	8.41	7.85	11.06	10.10	6.96	15.65	13.07	10.13	6.15	9.39	9.86	13.89	8.83	
1951	15.53	24.59	6.98	11.59	7.20	9.88	9.53	10.05	9.33	6.62	14.35	10.66	9.69	8.32	8.92	11.30	11.01	6.90	
1952	22.42	32.46	10.13	17.52	9.88	13.52	13.41	15.99	11.51	9.78	23.32	17.19	15.70	8.98	12.50	14.86	19.30	11.30	
1953	8.13	21.00	8.48	8.39	7.56	6.91	8.10	8.65	7.00	4.91	9.52	9.43	10.03	4.92	8.25	8.40	10.77	6.49	
1954	15.16	27.58	10.24	13.23	9.51	13.42	10.63	13.45	12.79	8.81	16.84	15.37	12.32	8.52	12.23	14.76	16.45	8.70	
1955	14.40	25.33	8.50	12.05	9.78	13.50	8.24	9.31	6.98	10.38	15.59	12.21	8.64	6.45	8.31	14.84	10.25	7.63	
1956	8.11	19.35	6.83	7.45	6.97	4.48	5.41	7.66	5.91	4.30	10.68	9.03	8.68	4.32	7.12	6.02	8.52	7.99	
1957	16.73	28.25	9.83	11.65	8.75	10.32	9.52	12.38	9.01	7.14	14.11	17.27	12.95	7.11	10.95	11.73	13.84	10.47	
1958	26.39	35.69	10.64	16.83	11.44	20.25	15.39	19.00	17.49	13.38	21.54	23.12	14.22	13.80	13.46	21.36	22.83	11.21	
1959	11.76	19.33	4.90	8.23	7.04	7.89	11.28	6.95	7.44	5.45	11.70	8.94	7.66	4.89	7.17	9.45	7.92	6.05	
1960	13.34	21.74	5.63	9.20	7.79	10.51	6.98	10.68	9.71	6.94	10.82	12.40	5.40	6.97	6.65	10.03	12.83	6.25	
1961	16.41	33.44	15.26	14.41	11.18	8.50	15.17	10.23	9.52	9.73	17.27	13.91	13.99	7.32	16.60	11.75	16.42	14.35	
1962	16.36	26.83	8.66	14.72	9.33	10.29	7.36	10.46	8.75	5.30	18.86	16.50	12.83	4.83	12.20	12.25	13.75	9.12	
1963	15.24	28.83	11.44	10.85	8.58	8.52	10.97	11.08	10.06	8.17	13.78	13.21	14.19	7.43	11.64	9.48	13.83	11.19	
1964	14.02	24.97	8.40	10.68	10.08	7.20	9.25	10.58	7.61	7.30	12.44	11.08	10.53	5.41	9.95	8.00	10.32	9.06	
1965	19.74	35.82	12.97	12.35	9.19	11.05	10.63	12.61	9.96	10.60	17.88	14.32	17.07	7.66	14.04	10.96	13.69	13.23	
1966	17.75	30.06	7.98	11.60	7.39	11.39	9.05	12.98	10.47	7.35	18.53	14.90	10.42	7.64	10.04	11.63	14.82	9.41	
1967	24.09	42.59	17.06	18.83	11.09	12.35	18.00	19.91	12.00	11.98	24.44	22.97	17.34	7.89	14.81	16.93	19.31	16.46	
1968	17.92	29.15	10.41	12.22	12.34	10.62	8.88	11.64	8.91	8.71	15.73	14.37	12.41	6.57	11.62	12.02	14.14	11.22	
1969	26.23	34.93	11.51	19.91	10.19	16.03	14.38	19.97	13.34	15.57	26.12	21.02	12.26	9.66	12.17	17.31	15.63	11.41	
1970	11.96	28.18	10.64	12.91	19.19	8.92	9.51	9.93	8.90	11.77	13.61	11.54	13.62	7.12	12.13	10.05	12.17	9.61	
1971	13.42	28.04	9.32	10.64	6.72	11.92	10.70	9.22	9.91	9.02	15.35	13.42	13.72	6.06	11.45	13.25	12.33	9.62	
1972	15.98	27.68	9.77	12.44	7.97	7.66	10.87	7.67	11.29	7.57	14.51	12.54	11.84	6.50	11.10	8.67	14.40	11.86	
1973	22.28	39.15	14.59	19.70	15.47	17.23	15.31	16.69	16.28	11.55	30.37	16.98	23.33	11.35	17.45	19.76	21.88	16.50	
1974	10.14	19.58	8.02	9.85	7.29	9.50	7.58	6.31	6.80	5.15	10.31	7.29	9.91	4.51	9.55	9.30	8.09	5.50	
1975	16.94	31.53	13.71	14.52	9.49	13.80	12.27	17.15	11.60	12.61	15.30	13.87	10.78	9.37	12.13	12.70	16.38	9.29	
1976	13.28	22.73	6.92	11.00	8.34	9.21	9.43	10.43	7.55	7.99	15.47	9.47	7.64	5.28	7.45	10.66	8.91	7.65	
1977	9.92	19.61	7.69	8.79	9.88	9.52	8.68	5.50	6.13	7.13	11.45	8.73	6.65	9.47	8.98	12.93	10.92	6.78	
1978	16.81	29.34	10.75	21.52	14.07	18.43	10.51	18.16	15.95	15.49	27.57	20.86	10.00	11.42	12.32	19.56	22.41	9.06	
1979	22.32	42.09	12.76	19.77	11.13	15.79	15.10	19.37	15.56	14.33	25.43	19.25	10.51	12.59	12.34	17.31	18.55	12.28	
1980	23.93	36.17	16.19	23.59	12.09	19.75	16.71	22.29	18.52	17.39	26.63	23.94	14.19	11.89	16.66	20.46	24.24	11.22	
1981	11.71	30.50	11.76	15.77	11.01	10.83	12.75	13.77	11.02	12.30	16.42	14.70	13.55	9.44	13.47	11.09	15.95	10.96	
1982	18.13	36.28	13.98	14.34	12.57	12.86	16.47	15.56	12.69	10.77	18.51	17.97	10.75	7.70	13.02	15.28	16.25	10.14	
1983	24.02	40.11	14.50	19.56	11.01	22.97	16.48	21.86	18.56	10.27	26.67	25.19	15.12	14.56	14.35	25.56	25.78	11.67	
1984	15.35	33.02	15.57	12.20	10.82	10.29	12.26	12.74	9.72	12.92	13.15	13.77	18.01	5.48	17.60	13.17	17.72	13.02	
1985	17.56	29.73	10.74	10.73	10.58	8.85	14.17	13.15	10.50	9.92	18.89	19.06	15.90	8.96	12.72	11.11	14.35	9.05	
1986	22.01	29.63	13.88	17.02	11.64	12.73	11.00	16.65	12.00	13.87	17.93	17.50	13.88	7.44	12.69	16.00	17.67	10.39	
1987	13.57	26.15	9.71	10.29	8.25	9.74	10.70	14.54	10.52	9.33	14.16	15.99	10.83	7.43	12.15	12.04	12.89	11.98	
1988	19.61	33.56	15.32	15.04	12.72	16.47	13.48	14.66	15.47	16.48	22.20	20.87	17.56	11.42	15.59	18.11	18.73	12.00	
1989	12.01	20.14	8.01	8.93	7.75	7.50	7.78	8.03	8.14	8.28	10.25	9.66	9.67	6.01	11.42	7.69	10.91	6.92	
1990	13.30	23.98	8.66	13.96	7.80	13.20	9.71	7.76	8.83	9.76	17.91	12.00	10.08	4.78	10.39	12.93	10.81	7.46	
1991	12.38	24.50	9.06	14.01	8.63	13.56	9.00	11.57	7.47	7.24	17.97	12.43	11.69	4.29	9.16	15.00	12.60	7.44	
1992	19.89	25.91	13.55	19.91	14.03	19.65	13.04	19.31	16.51	13.32	25.35	17.98	14.17	11.81	12.03	20.85	18.14	12.12	
Court	64	61	61	61	61	61	61	61	61	61	61	64	61	64	61	61	64	61	
Maximum	26.39	42.59	17.06	23.59	19.19	22.97	18.00	22.29	18.56	17.39	30.37	25.19	23.33	15.77	17.60	23.56	25.78	16.50	



Assembling isohyetal maps involves the following principles: 1) precipitation data from gaging station are used as control points, and 2) isolines are interpolated between stations. For the interpolation procedure, this study uses a method of estimation of random fields called Kriging. Conceptually, it estimates values of the precipitation field at a point/s from a limited set of observed values. Kriging is a very suitable technique for analyzing mountainous regions where the station-to-station variation of the precipitation as well as elevation are large (Bras et al., 1985). A mapping graphics software, SURFER (Golden Software, 1986), was utilized to carry out the interpolation procedure selecting the Kriging option. SURFER has a set of gridding algorithms that accept input data files with {x;y;z} coordinates. In this case, pairs of {x;y} coordinates represent longitude and latitude of the precipitation gaging stations respectively, whereas the {z} coordinate represents the climatological variable of interest, annual precipitation. An example data set for the gridding algorithm is provided in Table 10. Notice that the geographical coordinates of the gaging stations were converted to the Universal Transverse Mercator 12 (UTM 12) reference

Table 10. Example of Input Data for Gridding Algorithm

Site	Station Name	{y}:Latitude [UTM12]	{x}:Longitude [UTM12]	{z}:Mean Annual Precip.[in/yr]
(A)	ALTON	4143770	368764	16.34
(B)	BLOWHARD MTN R	4160990	336648	29.17
(C)	CEDAR CITY FA	4174680	314868	10.95
(D)	ENTERPRISE	4161000	260058	13.71
(E)	ENTERPRISE B J	4183030	266575	10.15
(F)	GUNLOCK PH	4129600	257673	12.06
(G)	HATCH	4167740	373554	11.15
(H)	KANAB	4101320	363651	12.99
(I)	LA VERKIN	4121110	298875	10.92
(J)	MODENA	4187430	243196	10.13
(K)	NEW HARMONY	4150770	296638	17.55
(L)	ORDERVILLE	4125500	355172	14.96
(M)	PAROWAN PP	4188700	338663	12.25
(N)	ST. GEORGE	4108890	270419	8.10
(P)	SUMMIT	4185180	329786	11.86
(Q)	VEYO PH	4136830	263793	13.43
(R)	ZION NP	4120550	324018	14.80
(S)	PANGUITCH	4186236	373838	9.89



coordinate system. The {z} coordinate corresponds to mean annual precipitation for the period [1932-1992].

The isohyetal map shown in Figure 11 depicts average conditions of annual precipitation in the study region for the period [1932-1992]. It was prepared based on data presented in Table 10. Each band represents an area of equal rainfall depth, ranging from 10 inches in the south-west portion of the study area (lowest elevation) to 29 inches as the largest concentration of average annual precipitation at the northern ridge of the North Fork of the Virgin River subarea (highest elevation). The study area displays a strong gradient of precipitation versus elevation, especially, in the NFVR subarea. It is estimated that annual precipitation increases on average 3.1 inches per 1,000 feet change in elevation.

The isohyetal map in Figure 11 was compared to the map prepared for the State of Utah by the U.S. Weather Bureau based on 1931-1960 precipitation data (Utah-DWR, 1983, pp.30). In general, both maps keep a very close resemblance, depicting the same orientation and magnitudes of the isohyetal lines. A noticeable difference occurs in the region with the highest precipitation, where a 40 inches isohyetal line is shown in the 1931-1960 Weather Bureau map encircling a small area. This difference can be attributed to two factors: 1) the isohyetal map presented in this study is based on a period of record twice as long as the previous map, and 2) a new gaging site has been reporting data since 1965, Site (B)-Blowhard Mtn Radar, which is located in the same area where the main discrepancy between the two maps appears.

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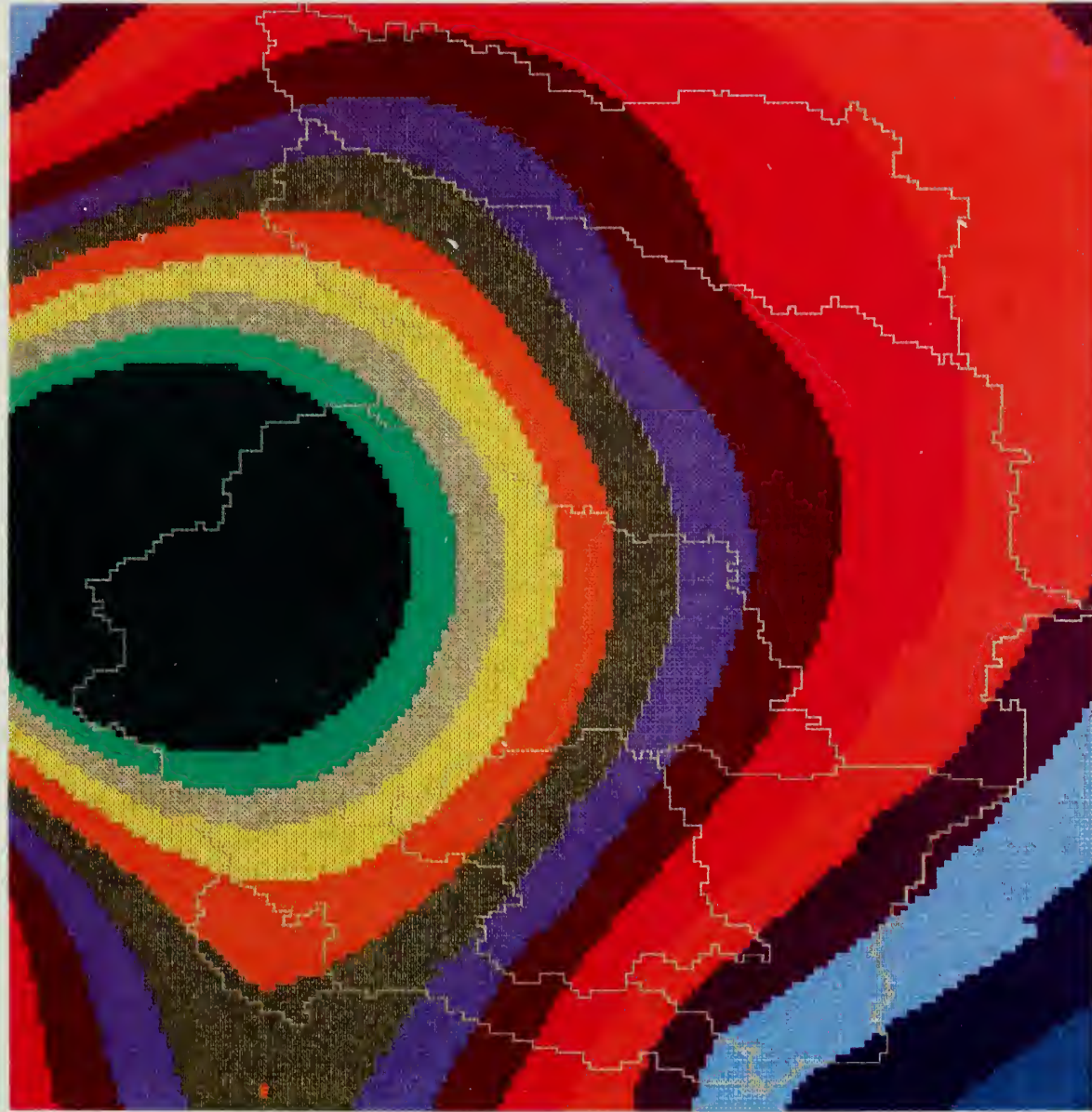
Fig.11 Areal Distribution of Precipitation (Isohyetal Map) - Period [1932-1992]

(next two pages)

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# Isobyyetal Map for 1932-1992



Idrisi



# Isohyetal Map for 1932-1992



Press PgUp	
22 inches	
23 inches	
24 inches	
25 inches	
26 inches	
27 inches	
28 inches	
29 inches	



## **7.0 APPLICATION OF THE METHODOLOGY**

### **7.1 Cases Under Analysis**

The link between precipitation and surface runoff can be investigated at different time scales, from the single flow event lasting minutes or hours to the aggregation of multiple flow events within the annual hydrological cycle. This study focuses on the longer time span. The investigation plan required the generation of several isohyetal maps of annual precipitation. In order to organize the analysis, the maps were grouped under the three following cases:

- Case I: Isohyetal maps of annual precipitation for single water-years, from 1932 to 1991. A total of 60 maps were generated.
- Case II: Isohyetal maps of mean-annual precipitation for water-years having concurrent records of precipitation and surface runoff. A total of fourteen maps were generated.
- Case III: An isohyetal map depicting the long-term spatial variability of mean annual precipitation in the Zion region during [1932-1992]. One map was generated.

Maps developed under Cases I and II are utilized for the numerical analysis presented in Section 7.2 and 7.3. The single map included as Case III was created for illustration purposes (see Figure 11 in this report), and for the estimation of long-term runoff at ungaged sites, presented in Section 7.5.

The transfer of precipitation information as described in Section 6.0 made possible the establishment of a database containing annual precipitation with values from 1932 to 1992. The database includes 18 precipitation gaging sites in the study region as shown in Figure 8. As part of the methodology, "concurrent periods of record" for precipitation and surface runoff are defined at river locations where USGS flow measurements exist. The period of flow record available at each site was adopted as the "concurrent period". The limiting factor in the definition of the concurrent period for most sites was the relatively short extension of the flow records. For instance, Site (8) - North Fork of the Virgin River below Bullock Canyon, has regional annual precipitation values from 1932 to 1992, while flow



measurements exist only for water-years 1975 to 1984. Consequently, the later ten-year concurrent period at Site (8) was adopted. Furthermore, as indicated in Section 6.1, 1932 was selected as the earliest water-year for back-extending precipitation records (the earliest isohyetal map generated for Case I corresponds to water-year 1932). This precludes the consideration of concurrent periods of record prior to 1932. Nevertheless, only Sites (12) and (15), with flow records starting in 1926 and 1910 respectively, are constrained by the 1932 cut-off date.

The results and analysis from Cases I and II are presented in Sections 7.2 and 7.3. Although both cases yield runoff coefficient values, their interpretation is different. Case I shows annual variations in the precipitation-runoff relationship, while results from Case II represent long-term water yield conditions at different locations in the Zion area. Another difference between the two cases are the flow records being used. Case I uses existing flows conditions (USGS records), whereas Case II uses the estimated mean-annual flows for natural conditions (virgin flows) provided in Table 1.

## **7.2 Analysis and Results for Case I**

Case I involves the computation of runoff coefficients, for single water-years, at the river locations listed in Table 1. Case I was included in the study plan to analyze the temporal variability of the annual " $k$ " coefficients (at several river sites) caused by the yearly changes in hydro-meteorological conditions. The basin's annual water yield is expected to vary annually due to changes in the volume of precipitation received as snowfall and summer thunderstorms. The amount and time distribution of precipitation affect soil moisture conditions and other factors controlling runoff, which in turn determine the volume of effective rainfall that reaching the basin's outlet.

The computations followed the procedure outlined in Section 3.3 and the GIS spatial analysis described in Figure 4. Results are presented in Table 11 and displayed graphically in Figure 12. Table 11 provides a summary of the output generated under Case I. Drainage areas listed below are slightly different than those reported in Table 1. The former were measured using the GIS raster format whereas those in Table 1 were estimated using the GIS vector format. Small differences are expected depending on the image pixel's size.



Table 11. Summary of Results for Case I

River Site	Period Analysis	Drainage Area [mi <sup>2</sup> ]	Precipit. Input [in-mi <sup>2</sup> ]	Excess Precipit. [Ac-Ft]	Range of "k" Values		Runoff Coefficient			
					Minimum	Maximum	Average	Sd.Dev	Cv	N <sub>y</sub>
					[ % ('9' ) ]		[ % ]	[ % ]	[ ]	[yr]
(1)	79 - 90	192.76	3196.4	10,568.	3.90 ('88)	8.82 ('80)	6.15	1.24	0.20	12
(2)	67 - 91	74.19	1342.7	14,015.	10.96 ('88)	41.86 ('79)	19.27	6.96	0.36	25
(3)	92	347.83	6325.5	36,190.			10.76			1
(4)	88 - 91	6.58	158.6	1,187.	8.90 ('91)	19.25 ('88)	13.65	4.48	0.33	4
(5)	88 - 91	9.21	215.4	2,051.	10.88 ('90)	25.11 ('88)	17.21	5.62	0.33	4
(6)	57 - 61	9.97	196.3	5,234.	22.20 ('61)	76.22 ('58)	47.02	22.53	0.48	5
(7)	73 - 78	5.64	125.7	3,624.	29.85 ('77)	69.53 ('78)	52.87	14.06	0.27	6
(8)	75 - 84	28.68	729.2	14,307.	19.80 ('77)	57.41 ('80)	35.18	10.51	0.30	10
(9)	79 - 84	43.82	1218.8	18,546.	17.28 ('82)	39.11 ('80)	27.97			6
(10)	92	287.83	5826.1	51,940.			16.76			1
(12)	32 - 88	343.59	7013.4	74,502.	10.15 ('61)	33.52 ('80)	19.27	5.68	0.29	57
(14)	86 - 91	94.78	1409.3	4,455.	3.39 ('90)	6.82 ('86)	5.82	1.18	0.20	6
(15)	32 - 91	943.78	16250.7	33,894.	9.92 ('63)	27.28 ('79)	15.10	3.85	0.25	53
(16)	86 - 91	96.85	1466.2	6,105.	5.97 ('90)	9.55 ('88)	7.55	1.42	0.19	6

Precipitation input in Table 11 represents the total volume of water collected by the catchment. It is computed independently for each water-year by means of the denominator of Eq.(1). Precipitation input as indicated in Table 11 is the average of all those annual volumes. The excess precipitation column is the portion of the precipitation input that becomes runoff. There are as many annual values per site as years of flow record available. The values indicated in Table 11 are the average of all the measured annual flows. From each pair of "precipitation input" and "excess precipitation" values the annual runoff coefficient "k" is computed. Table 11 indicates the range between the maximum and minimum k values computed at each site and the water-year at which they occurred in parenthesis. The last three columns show the average annual runoff coefficient (an estimate of long-term conditions), the standard deviation and coefficient of variation (an estimate of its variability), and the sample size N<sub>y</sub> (an indicator of the reliability of the previous two statistics).

k values vary noticeably from year to year and from site to site. The variability in the annual runoff coefficient at a given site can be attributed to the periodic stochastic meteorological processes. This is the case for the North Fork of the Virgin River subarea, where, although we have no data to substantiate the following statement, it is believed that



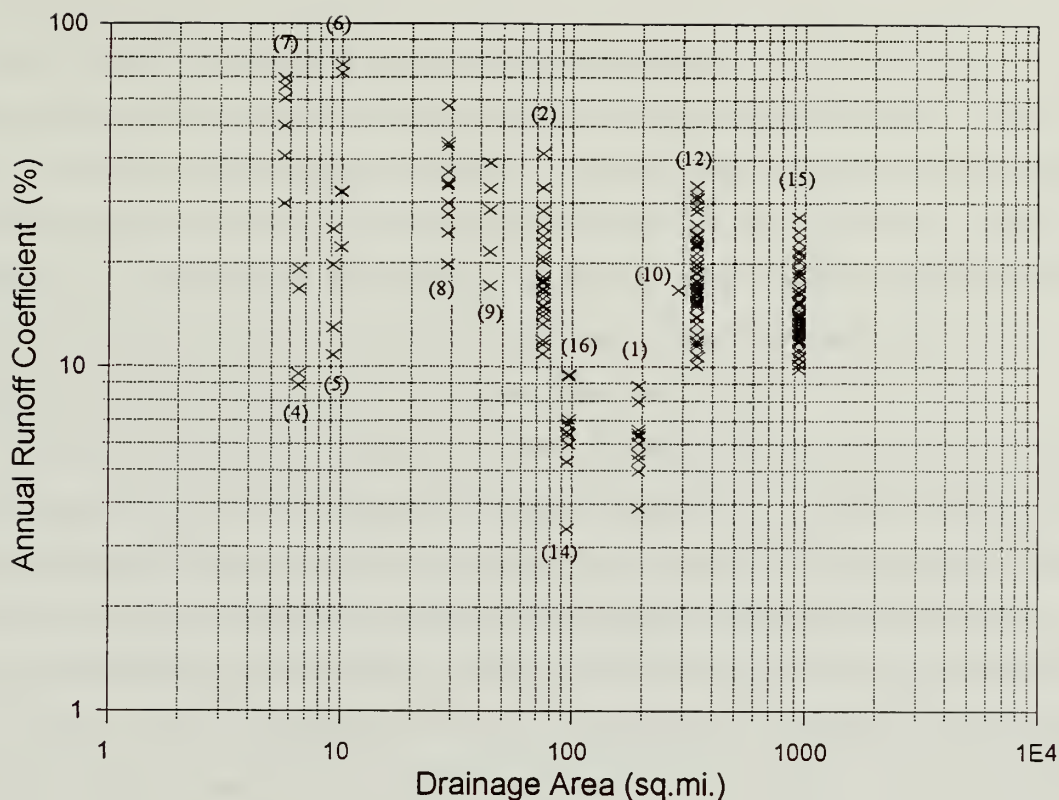


Fig.12 Annual Variability of Runoff Coefficients - Case I

no significant changes in the basin's land use took place during the flow measuring years. Moreover, it is assumed that water diversion practices have remained practically unchanged for many years. The largest senior water rights in the NFVR basin have priority dates that precede the turn of the century.

Table 11 shows  $k$  values as low as 3.9% at Site (14) during 1980 (the second driest year on record), to as high as 76.2% at Site (6) during 1958 (a very wet year). Water-years 1979 and 1980, the wettest 2-years period on record, appear repeatedly in Table 11 as the water-years with the maximum  $k$  value. Other areas of the Upper Virgin River Basin have been subject to more accelerated water depletions than the NFVR, mainly to the west of the Park. It is believed that these changes may have modified the relationship between precipitation and runoff along the years.



Notice the increase in dispersion of the " $k$ " coefficient displayed in Figure 12 as the size of the drainage area decreases (larger standard deviations). Catchments with the smallest drainage areas are the ones located at high altitude and with the shortest periods of record. The basis for this finding is two fold. 1) Not enough years of record are available to accurately assess the dispersion of the annual values at the small catchments, and 2) small watersheds have a relatively small probability of being impacted by severe storms producing large runoff events every year. Contrarily, large basins tend to average hydro-meteorological conditions more due to the large areas they cover.

Notice also the different range of  $k$  values obtained at Sites (1), (14), (16), (4) and (5) in comparison with the remaining sites plotted in Figure 12. It is speculated that changes in hydro-geological conditions across the region can be a main factor responsible for these differences. The Park is located in an area with impressive geological formations and diverse geomorphological characteristics. Soils in the region are unevenly distributed and vary in quantity, quality, and depth (SCS, 1977). Regional soil maps show drastic changes in soil characteristics, ranging from poorly to excessively drained soils. No formal attempt was made in this study to include soil type as an explanatory variable of the regional variability of the runoff coefficients. However, a geologic map of the Zion region (USGS, 1950) shows basalt formations are present along the rivers' path and/or at the headwaters of the catchments with the smaller  $k$  values. A detailed hydro-geological study is necessary to determine whether fractured basal formations in particular areas can be responsible for the noticeable decrease in water yield.



### 7.3 Analysis and Results for Case II

Case II was included in the study plan to analyze the spatial variability of the runoff coefficient in the Zion region under "average" hydro-meteorological conditions. Mean values of runoff coefficients, denoted as  $\bar{k}$ , are estimated for this purpose. This section devotes special attention to the sites located along the North Fork and the Virgin River, from Site (7) to Site (15), see Figure 5. The main objective is to develop a mathematical relationship connecting the basins' water yield to geomorphological and climatological characteristics of the river basin.

The areal variability in mean-annual precipitation depicted by the isohyetal maps is related to mean-annual runoff conditions at specific river locations. Table 12 contains the information to generate the isohyetal maps for Case II. It shows the concurrent period of record adopted at each river site, and provides the mean-annual precipitation (during the concurrent period) for eighteen precipitation stations. For instance, the entry 17.56 inches/year at the (A) Alton station is obtained as average of the annual precipitation amounts provided in Table 9 for the years 1979 to 1992. Each row of values in Table 12 generates one isohyetal map. River sites (3) and (10) have a concurrent period of record for one water-year, 1992. Both stations are considered ungaged in this study.

The computational procedure for Case II follows the same steps as in Case I. Results are presented in Table 13. The precipitation input is now a single number per site. It is important to emphasize that excess precipitation under Case II reflects natural flow conditions in the streams instead of existing (USGS) flows as in Case I (see Section 5.2 for the estimation of natural flow conditions). The coefficients  $\bar{k}$  are computed by means of Eq.(1), indicating long-term water yield conditions at each site. The  $\bar{k}$  values listed in Table 13 are analogous in nature but different in magnitude to the average  $k$ 's listed in Table 11.  $\bar{k}$  is always larger than the average  $k$ 's. This is due to the utilization of natural flows for the computation of the  $\bar{k}$  values in contrast to existing flow conditions used to compute the average  $k$ 's.



Table 12. Precipitation Data (in/yr) to Generate Isohyetal Maps for Case II.

River Site	Concurrent Period	Precipitation Gaging Stations																	
		(A) Alton	(B) Blowh	(C) Cedar C.	(D) Enterp	(E) Enterp B.	(F) Gaulock	(G) Hatch	(H) Kanab	(I) La Verk.	(J) Modena	(K) New Har.	(L) Ondervil	(M) Parowan	(N) St.Georg	(P) Summit	(Q) Veyo Ph.	(R) Zion NP	(S) Pangu.
(1)	79-92	17.56	30.84	12.41	15.37	10.72	13.87	12.76	15.09	12.54	11.87	19.53	17.17	13.28	8.84	13.11	15.33	16.76	10.48
(2)	67-92	17.11	30.16	11.70	14.90	10.85	13.05	12.11	13.99	11.70	11.18	18.99	15.90	12.90	8.42	12.49	14.53	15.81	10.45
(3)	92	19.89	25.91	13.55	19.91	14.03	19.65	13.04	19.31	16.51	13.32	25.35	17.98	14.17	11.81	12.03	20.85	18.14	12.12
(4)	88-92	15.44	25.62	10.92	14.37	10.19	14.07	10.60	12.27	11.28	11.02	18.74	14.59	12.63	7.66	11.72	14.92	14.24	9.19
(5)	88-92	15.44	25.62	10.92	14.37	10.19	14.07	10.60	12.27	11.28	11.02	18.74	14.59	12.63	7.66	11.72	14.92	14.24	9.19
(6)	57-61	16.93	27.81	9.25	12.06	9.24	11.49	11.67	11.85	10.63	8.53	15.09	15.13	10.84	8.02	11.01	12.86	14.77	9.66
(7)	73-78	14.90	26.99	10.28	14.23	10.76	12.95	10.63	12.37	10.72	9.99	18.41	12.87	11.38	8.57	11.31	14.15	14.77	9.13
(8)	75-84	17.24	32.14	12.38	16.11	11.04	14.35	13.07	15.68	12.73	12.12	19.86	16.78	11.72	9.72	12.83	15.67	17.71	10.21
(9)	79-84	19.24	36.36	14.13	17.54	11.44	15.42	14.96	17.60	14.35	13.00	21.47	19.14	13.69	10.28	14.57	16.81	19.75	11.55
(10)	92	19.89	25.91	13.55	19.91	14.03	19.65	13.04	19.31	16.51	13.32	25.35	17.98	14.17	11.81	12.03	20.85	18.14	12.12
(12)	26-88	16.58	29.56	11.03	13.67	10.20	11.96	11.24	13.09	10.96	10.16	17.53	15.23	12.31	8.21	11.94	13.38	15.13	9.99
(14)	86-92	16.11	26.27	11.17	14.17	10.12	13.26	10.67	13.22	11.28	11.18	17.97	15.20	12.55	7.60	11.92	14.66	14.54	9.76
(15)	10-71	16.62	29.44	11.05	13.67	10.13	12.04	11.21	13.16	10.93	10.19	17.52	15.38	12.35	8.09	11.94	13.44	15.04	9.94
(16)	86-91	15.48	26.33	10.77	13.21	9.46	12.20	10.28	12.20	10.41	10.83	16.74	14.74	12.29	6.90	11.90	13.63	13.94	9.37



Table 13. Summary of Results for Case II

River Site	Period Analysis 19__	Elevation [ft]	Drainage Area [mi <sup>2</sup> ]	Precipitat. Input [in-mi <sup>2</sup> ]	Excess Precipit.(*) [Ac-Ft]	$\bar{k}$ [%]
(1)	79 - 92	5,060.	192.76	3237.73	10,819.	6.28
(2)	67 - 92	5,900.	74.19	1253.32	14,051.	21.08
(4)	88 - 92	7,680.	6.58	160.70	1,209.	14.14
(5)	88 - 92	7,640.	9.21	212.51	2,053.	18.16
(6)	57 - 61	8,320.	9.97	162.11	5,237.	60.73
(7)	73 - 78	7,530.	5.64	112.18	3,800.	63.68
(8)	75 - 84	6,420.	28.68	630.75	15,207.	45.33
(9)	79 - 84	6,000.	43.82	1050.97	19,808.	35.43
(12)	32 - 88	3,970.	343.59	6351.27	78,294.	23.18
(14)	86 - 92	3,680.	94.78	1376.70	4,901.	6.69
(15)	32 - 92	3,440.	943.78	15387.12	151,622.	18.53
(16)	86 - 91	3,040.	96.85	1359.68	8,032.	11.11

(\*) Estimated Natural Flows, see Section 5.2

After computing the  $\bar{k}$  coefficients a mathematical relationship was developed between the basin's runoff coefficients and some observable or measurable explanatory variables. By this approach, estimation of water yield at any river site (within the domain of the derived model) in the absence of flow observations becomes possible. The river sites used in the correlation analysis are located along the North Fork and the Virgin River. Ideally, the derivation of long-term water yield conditions requires sites with long records like Sites (12) and (15). However, given the characteristics of the analysis, no stations were eliminated because of short period of record. More is to be gained by use of all possible data. Even stations with less than 10 years of data, like Sites (7), (8) and (9), recorded the driest and the wettest water-years ever measured at the NFVR basin (see Figure 3 in Diaz, 1993, for more information on this subject). This situation allows for the behavior of the watershed to be assessed under normal and extreme hydrological conditions. The selected stations range from the small drainage area at Site (7) to the station at Site (15) which encompasses the largest contributing drainage area. Sites (4) and (5) were excluded because of their peculiar hydro-geologic conditions. Sites (1), (2), (14) and (16) were also excluded for being located outside of the limited geographical area defined for the correlation analysis.



Three sets of points are shown in Figure 13 (using two vertical scales), all representing average-annual conditions. They are: total precipitation ( $\blacktriangle$ ), surface runoff ( $\times$ ), and water yield ( $\blacksquare$ ) versus drainage area. As expected, the  $\bar{k}$  points are aligned in a decreasing trend. As drainage area increases water yield decreases. The smaller catchments located in the headwaters of the NFVR subarea, with large terrain gradients and short concentration times, experience a quick runoff response. This quick runoff response translates into larger water yields of the watersheds. Moreover, the larger precipitation concentration occurs in the high altitude terrain, decreasing smoothly with elevation (see Figure 11). Figure 13 shows the precipitation line slightly steeper than the surface runoff line (in the log-10 domain). In other words, precipitation increases faster than runoff as we move downstream into the basin. The convergency of the two curves predicts a larger reduction in runoff at lower elevations for a percentage change in climatic conditions.

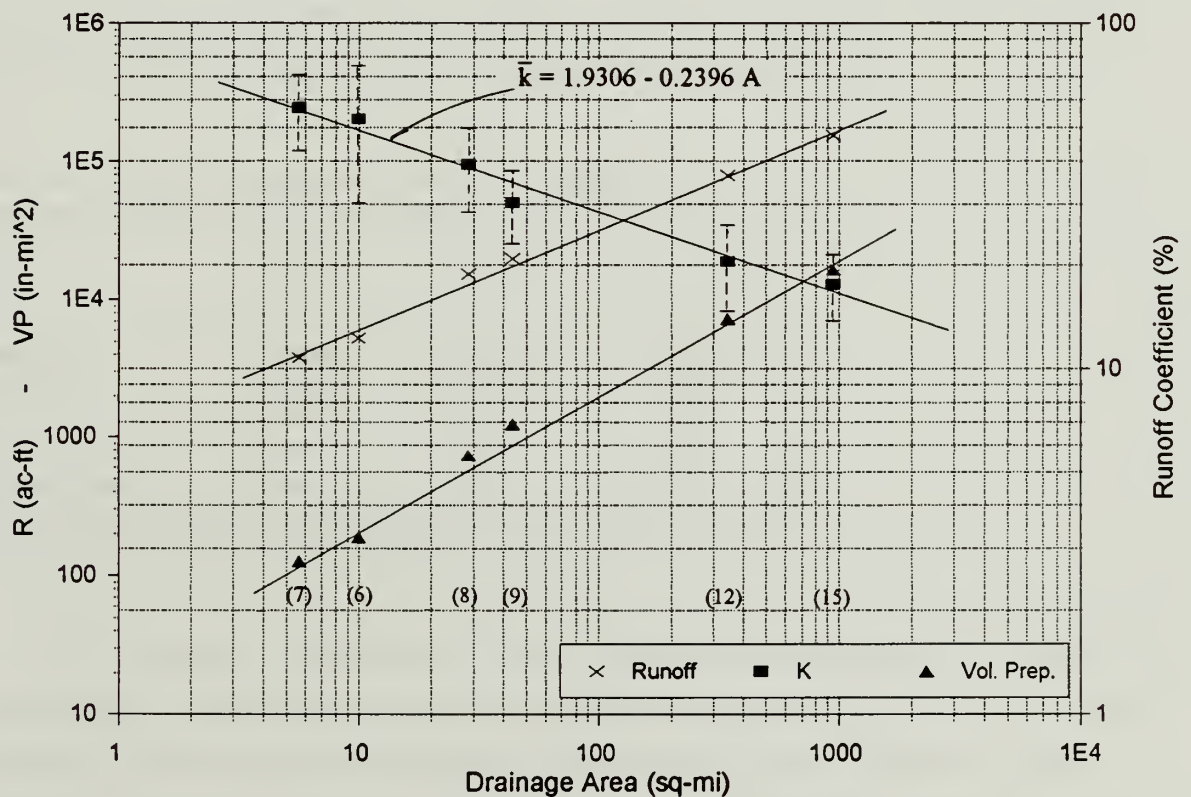


Fig.13 Runoff Coefficient vs. Explanatory Variables - Case II



#### 7.4 Regression of Runoff Coefficients

Many studies have related discharge to catchment physiographic and climatic variables. However, because of the intrinsic characteristic of each study area, no general agreement was reached as to identify the most important explanatory variables. In this investigation, simple and multiple linear regression was used to relate water yield with a simple but comprehensive climatological index, i.e., mean-areal precipitation, and a physiographic component, i.e., drainage area. The regression model takes the form,

$$\text{Log}(\bar{k}) = a + b \text{Log}(VP) + c \text{Log}(A) \quad (15)$$

where  $a$ ,  $b$  and  $c$  are the least-square estimates of the parameters of the model.  $A$  [ $\text{mi}^2$ ] denotes the area of the catchment draining to the site where  $\bar{k}$  [%] is computed, and  $VP$  [ $\text{inches-mi}^2$ ] is the average-annual volume of precipitation collected in the watershed. Results of the regression analysis are shown in Table 14, where all inputs and outputs from the regression analysis are expressed in the logarithmic domain, base-10.

Table 14. Results of Regression Analysis - Case II

	(a) $\bar{k} = f(A)$	(b) $\bar{k} = f(VP)$	(c) $\bar{k} = f(VP, A)$	
Intercept (a)	2.27988	1.93064	2.4502	
Slope (b,c)	-0.24876	-0.23958	-0.37177, 0.11983	
$R^2$	0.992	0.977	0.994	
Std. Error Y	0.021	0.036	0.022	
Std. Error Coeff	0.011	0.019	0.132, 0.129	(16)

Note: Parameters of regression model in base-10 logarithmic domain

Both explanatory variables were highly significant within the North Fork and Virgin River stations. This is expected since they represent the typical cause and effect type of relationship, where precipitation is the basic causal factor of runoff together with basin morphology. The three predictive equations, (16.a), (16.b), and (16.c) show high values of the coefficients of determination  $R^2$ . They are equally suitable for predicting long-term



runoff coefficients within the geographical domain of the derived regression model. Practically all variance (99%) is explained by the explanatory variables, individually or in combination. Hence, the inclusion of any other new independent variable would be of very little significance. The regression line of  $\bar{k} = f(A)$ , Eq.(16.a) is shown in Figure 13. The annual variability of the  $k$  values (computed under Case I, see Table 11) is also shown in Figure 13 as  $\pm$  one standard deviation above and below the regression line.

Basin elevation, although not explicitly used as an explanatory variable in Eq.(15), has been implicitly incorporated into the analysis when computing mean-areal precipitation (see Section 3.3). Soil conditions were not part of the analysis because of the difficulties of obtaining a GIS layer of soils types. Nevertheless, it has been shown unnecessary within the limited study area of the regression model. The effect of soil and geology characteristics would be highly important if a predictive relationship were developed for the whole Upper Basin of the Virgin River.

## **7.5 Estimation of Mean-Annual Runoff at Ungaged Site**

The National Park Service chose an intermediate reach of the North Fork of the Virgin River to carry out biological and channel processes studies. The location of this site is indicated in Figure 5 as Site (10). Recently, the USGS installed a flow gaging station at the site. Flow records are available for only one water-year, 1992. See Table 1 for more information related to this site. Site (10) is considered ungaged for this study, and will be used to demonstrate the procedure to estimate mean-annual flows at ungaged sites.

The drainage area for Site (10) was delineated from topographic maps and digitized into the GIS for further manipulation and analysis. The volume of precipitation input is computed following the steps indicated in Figure 4. The isohyetal map from Case III, Figure 11, is used to estimate precipitation input. It is expected that the 61 years of precipitation available for the region, from 1932 to 1992, will yield a reliable estimate of the mean-annual runoff conditions at Site (10). The expected annual runoff at an ungaged site is determined by applying the corresponding runoff coefficient to the total precipitation input collected by the catchment up to that point. From the GIS spatial analysis, drainage area and



precipitation input for Site (10) are calculated as,

$$A = 287.82 \text{ mi}^2$$

$$VP = \sum_{i=17}^{29} A_i P_i = 6,344. \text{ inches-mi}^2$$

where  $\sum_{i=17}^{29}$  indicates that the drainage area is covered by 13 isohyet bands, ranging from 17

to 29 inches. See Figure 11 for further illustration. Alternatively, when the more accurate GIS computational procedure for the estimation of precipitation input is not readily accessible, the analyst can use Figure 14 as a substitute. Figure 14 establishes a correlative association between precipitation input and the basin drainage area. The regression line was

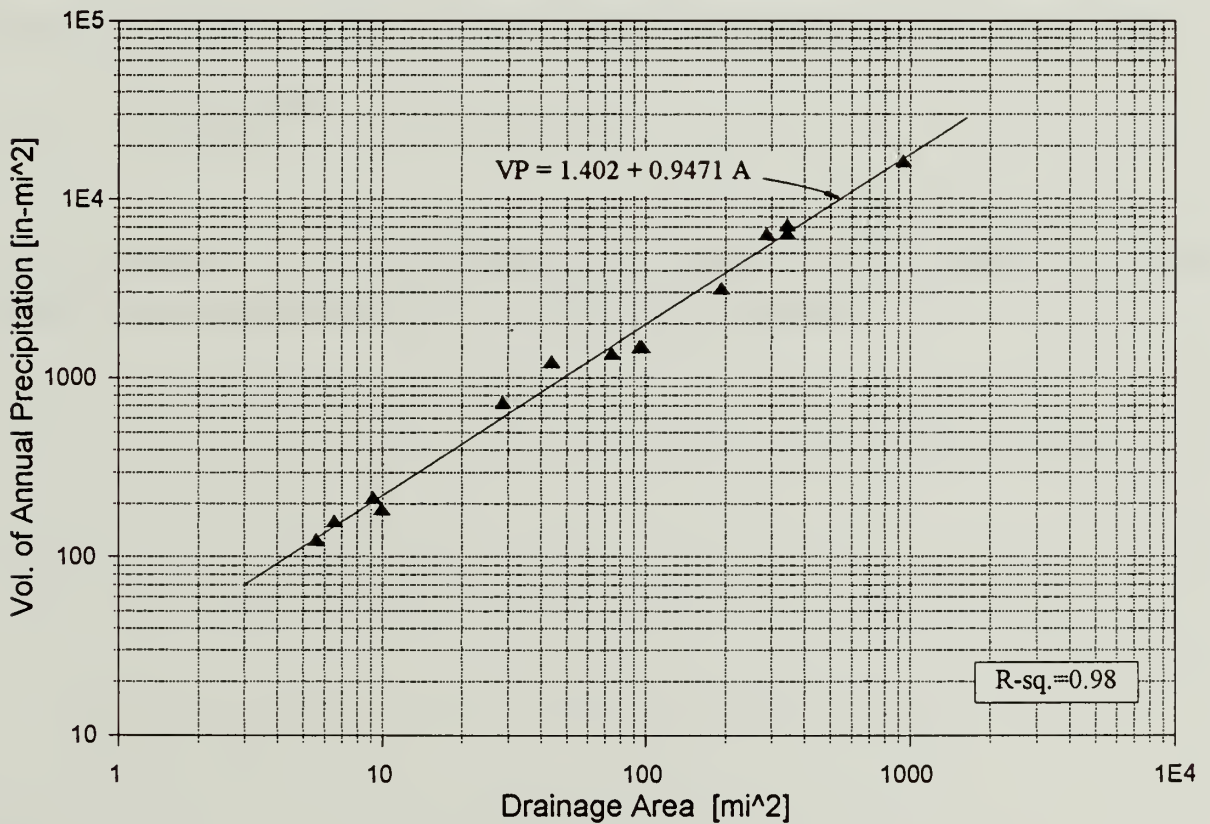


Fig.14 Precipitation Input vs. Drainage Area, Long-Term Conditions



developed using all flow gaging sites in the study area. The linear regression equation in Figure 14 is given by,

$$\text{Log}(VP) = 1.402 + 0.9471 \text{ Log}(A)$$

where  $VP$  and  $A$  are expressed in the log-10 domain, and in [in-mi<sup>2</sup>] and [mi<sup>2</sup>] respectively. Replacing the values of  $VP$  and  $A$  from the previous page in Equation (16.c), an estimate of the mean-annual runoff coefficient at Site (10) is obtained,

$$\text{Log}(\bar{k}) = 2.4502 - 0.37177 \text{ Log}(6,344) + 0.11983 \text{ Log}(287.83)$$

which yields,

$$\bar{k} = 21.4 \%$$

Finally, by transposing terms in Eq.(1), the mean-annual runoff at Site (10) is computed,

$$\bar{R} = \frac{0.214 \times 6,344.}{0.0188} = 72,200. \text{ Ac-Ft}$$

In summary, the runoff coefficient and mean-annual runoff for natural flow conditions at Site (10) are estimated as 21.4% and 72,200. ac-ft respectively.



## 8.0 LITERATURE CITED

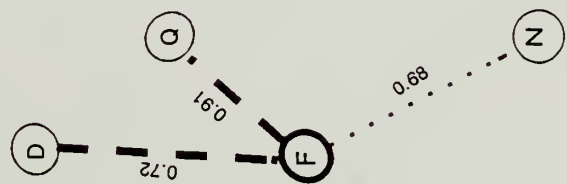
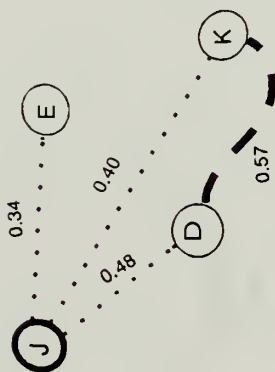
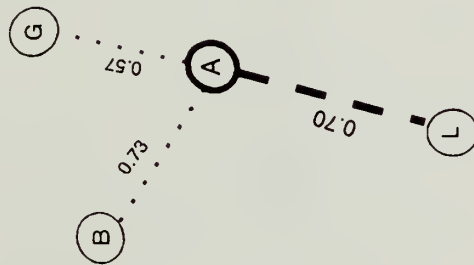
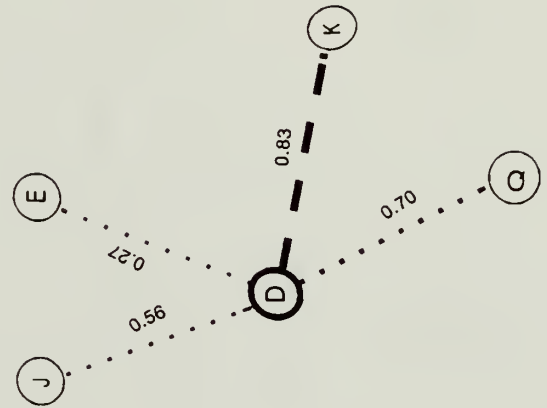
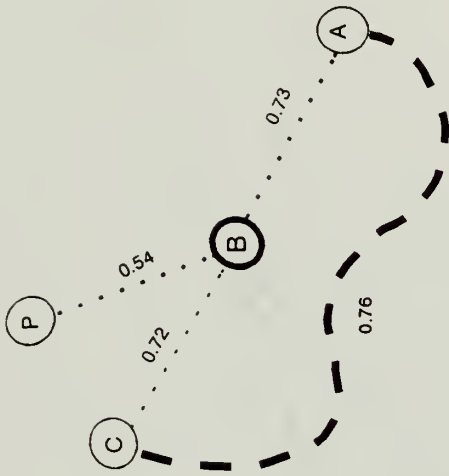
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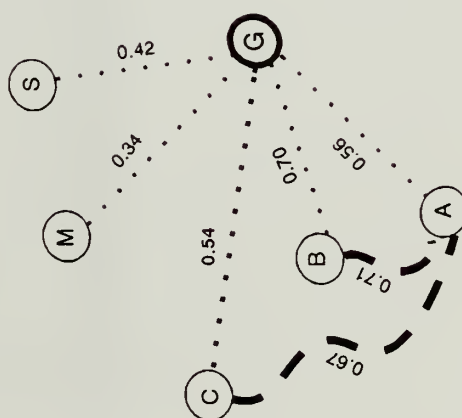
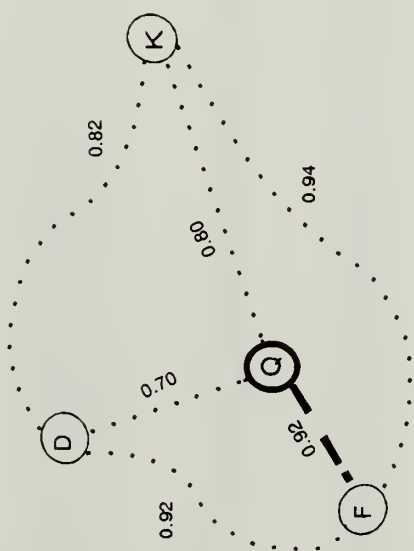
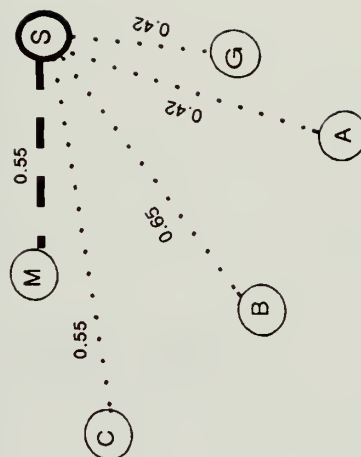
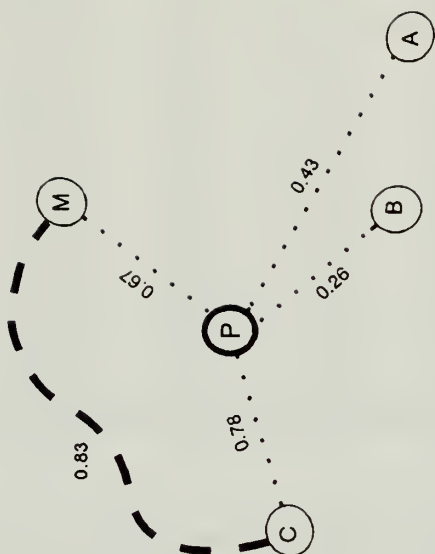
## Appendix I : Additional Results from Precipitation Data Transfer













## Appendix II : Annual Flows at USGS Gaging Stations in the Study Area

### 09403600 - KANAB CREEK NEAR KANAB, UT

Wtr-Yr	Total	Mean	Max.	Min.	Ac-Ft
1979	6191	17.0	190.0	4.1	12281
1980	10546	29.0	354.0	4.8	20920
1981	5331	14.6	94.0	5.0	10576
1982	4720	13.0	43.0	3.2	9403
1983	7968	21.9	116.0	3.8	15806
1984	4555	12.5	100.0	3.6	9036
1985	5444	14.9	65.0	5.4	10799
1986	4810	13.3	81.0	3.0	9542
1987	4150	11.4	22.0	5.2	8233
1988	3693	10.1	41.0	3.5	7326
1989	3303	9.1	90.0	3.1	6552
1990	3197	8.8	49.0	3.9	6342
1991	2908	8.0	20.0	3.2	5770
1992	2918	8.0	23.0	4.4	5790
Avg.	4981	13.7	92	4.0	9884

### 09404450 - EAST FORK VIRGIN RIVER NR GLENDALE, UTAH

Wtr-Yr	Total	Mean	Max.	Min.	Ac-Ft
1967	6963	19	239	12	13811
1968	6712	18	34	10	13313
1969	13035	36	202	12	25855
1970	5731	16	24	8.6	11367
1971	5044	14	27	7.9	10005
1972	4866	13	155	7.2	9652
1973	9300	25	155	12	18446
1974	5051	14	31	7.6	10019
1975	5318	15	29	8.5	10547
1976	4729	13	54	8.0	9380
1977	3849	11	24	7.0	7634
1978	7003	19	70	8.6	13890
1979	13273	36	211	11	26327
1980	16905	46	285	15	33531
1981	6927	19	36	9.6	13739
1982	6476	18	47	11	12845
1983	15042	41	215	13	29835
1984	7159	20	68	9.7	14199
1985	6688	18	41	4.3	13266
1986	6048	17	63	4.7	11995
1987	5305	15	27	4.7	10521
1988	4773	13	34	4.8	9468
1989	3751	10	32	3.3	7441
1990	3443	9.4	21	3.4	6831
1991	3261	8.9	26	4.8	6470
1992	4057	11.1	29	3.9	8050
Avg.	6950	19.1	84	8.2	13786

**Note:** Total, Mean, Max and Min flows expressed in [cfs]



**09404900 - EAST FORK VIRGIN RIVER NR SPRINGDALE, UT**

Wtr-Yr	Total	Mean	Max.	Min.	Ac-Ft
1992	18248	49.9	130	35	36190
Avg.	18248	49.9	130	35	36190

**09405200 - DEEP CREEK NEAR CEDAR CITY, UTAH**

Wtr-Yr	Total	Mean	Max.	Min.	Ac-Ft
1988	1083	3.0	13	0.84	2148
1989	560	1.5	5.8	0.32	1112
1990	381	1.0	5.4	0.21	757
1991	367	1.0	4.0	0.20	729
1992	656	1.8	10.0	0.23	1300
Avg.	609	1.7	7.6	0.36	1209

**09405250 - EAST FORK DEEP CREEK NR CEDAR CITY, UTAH**

Wtr-Yr	Total	Mean	Max.	Min.	Ac-Ft
1988	1926	5.3	29	1.1	3820
1989	895	2.5	7.9	0.14	1776
1990	585	1.6	4.6	0.20	1161
1991	730	2.0	7.9	0.55	1448
1992	1039	2.8	19.0	0.62	2060
Avg.	1035	2.8	13.7	0.52	2053

**09405300 - CRYSTAL CR NR CEDAR CITY UTAH**

Wtr-Yr	Total	Mean	Max.	Min.	Ac-Ft
1957	3750	10	210	0.20	7439
1958	5523	15	272	1.4	10955
1959	1246	3.4	38	0.40	2471
1960	1389	3.8	51	0.50	2756
1961	1284	3.5	54	0.90	2547
Avg.	2638	7.1	125	0.68	5237

**09405400 - NF VIRGIN R.NR.GLENDALE,UTAH**

Wtr-Yr	Total	Mean	Max.	Min.	Ac-Ft
1973	2967	8.2	30	2.1	5881
1974	1544	4.2	10	0.58	3063
1975	1592	4.4	10	0.80	3157
1976	1407	3.8	8.6	1.6	2791
1977	734	2.0	4.3	0.36	1455
1978	2719	7.5	39	0.71	5394
Avg.	1827	5.0	16.9	1.03	3624



**09405420 - N FK VIRGIN R BLW BULLOCH CANYON NR GLENDALE**

Wtr-Yr	Total	Mean	Max.	Min.	Ac-Ft
1975	4589	13	26	5.6	9101
1976	3716	10	21	5.6	7371
1977	2349	6.4	31	2.9	4660
1978	6690	18	71	3.6	13270
1979	9210	25	122	7.6	18268
1980	13706	37	200	14	27185
1981	6000	16	38	8.2	11901
1982	6462	18	55	6.5	12817
1983	11636	32	161	9.2	23080
1984	7772	21	44	6.6	15415
Avg.	7213	19.6	77	7.0	14307

**09405450 - N. FORK VIRGIN R. ABV ZION NARROWS NR GLENDALE, UT**

Wtr-Yr	Total	Mean	Max.	Min.	Ac-Ft
1979	10553	29	130	9.0	20932
1980	14011	38	200	14	27790
1981	5709	16	41	2.2	11323
1982	5536	15	54	6.0	10980
1983	12779	35	147	6.0	25347
1984	7515	21	45	6.5	14905
Avg.	9351	26	103	7.3	18546

**09405490 - N FK VIRGIN RIVER AB BIG BEND NR SPRINGDALE, UT**

Wtr-Yr	Total	Mean	Max.	Min.	Ac-Ft
1992	26188	71.6	329	30	51940
Avg.	26188	71.6	329	30	51940

**09405500 - NORTH FORK VIRGIN RIVER NEAR SPRINGDALE, UTAH**

Wtr-Yr	Total	Mean	Max.	Min.	Ac-Ft
1926	41284	113	710	42	81886
1928	30236	83	750	26	59972
1929	30276	83	500	24	60052
1930	27554	75	428	34	54653
1931	21338	58	1140	33	42323
1932	60293	165	1500	35	119589
1933	33122	91	759	46	65696
1934	18348	50	192	34	36393
1935	44812	123	1030	35	88883
1936	32671	89	620	33	64802
1937	70442	193	2070	37	139720
1938	57827	158	3000	50	114698
1939	28474	78	1400	32	56477
1940	29467	81	1000	30	58447
1941	70361	193	2000	35	139559
1942	52343	143	1180	45	103821
1943	37316	102	734	37	74015
1944	44227	121	966	28	87723
1945	36039	99	482	40	71482



Wtr-Yr	Total	Mean	Max.	Min.	Ac-Ft	(continuation)
1946	23010	63	558	29	45640	
1947	39845	109	800	36	79031	
1948	27983	76	487	32	55503	
1949	39287	108	655	30	77925	
1950	29555	81	354	36	58621	
1951	20089	55	393	35	39846	
1952	68252	186	1600	39	135376	
1953	21331	58	224	35	42309	
1954	30625	84	565	35	60744	
1955	22869	63	602	26	45360	
1956	19979	55	304	28	39628	
1957	29064	80	391	29	57648	
1958	59350	163	1290	36	117719	
1959	21369	59	311	33	42385	
1960	20375	56	161	27	40413	
1961	20007	55	1300	26	39683	
1962	39140	107	670	33	77633	
1963	19494	53	386	25	38666	
1964	24475	67	338	32	48545	
1965	37965	104	884	32	75302	
1966	35899	98	538	39	71205	
1967	42019	115	4990	35	83343	
1968	41710	114	600	40	82731	
1969	73249	201	1270	43	145287	
1970	25321	69	483	38	50223	
1971	26811	73	435	34	53179	
1972	25877	71	930	33	51326	
1973	63999	175	1270	38	126940	
1974	20786	57	151	24	41228	
1975	30305	83	884	30	60109	
1976	22775	62	379	29	45174	
1977	15254	42	247	23	30256	
1978	53958	148	877	29	107024	
1979	68249	187	1220	28	135370	
1980	89815	245	3000	38	178145	
1981	33359	91	694	40	66167	
1982	39523	108	801	33	78393	
1983	88828	243	1730	48	176188	
1984	36969	101	352	41	73327	
1985	47347	130	758	42	93911	
1986	35507	97	472	37	70427	
1987	29094	80	370	34	57707	
1988	39671	108	561	31	78686	
Avg.	38175	104.5	899	34	75718	

**09405900 - NORTH CREEK NEAR VIRGIN, UTAH**

Wtr-Yr	Total	Mean	Max.	Min.	Ac-Ft
1986	3073	8.4	112	0.00	6095
1987	2268	6.2	66	0.00	4499
1988	3390	9.3	203	0.00	6724
1989	1844	5.1	137	0.00	3657
1990	1095	3.0	91	0.00	2173
1991	1807	4.9	165	0.00	3579
1992	3819	10.4	242	0.00	7580
Avg.	2471	6.8	145	0.0	4901



**09406000 - VIRGIN RIVER AT VIRGIN, UTAH**

Wtr-Yr	Total	Mean	Max.	Min.	Ac-Ft
1910	112738	309	2770	80	223612
1911	161146	441	10600	60	319628
1912	68579	187	5100	104	136024
1913	79544	218	8100	84	157773
1914	108900	298	2500	82	216000
1915	93836	257	4360	80	186121
1916	142450	389	3300	117	282545
1917	82048	225	2610	39	162740
1918	84207	231	3690	42	167022
1919	67601	185	1720	55	134085
1920	85145	233	3000	22	168883
1921	80588	221	2140	22	159844
1922	169907	465	2020	79	337005
1923	139808	383	2320	52	277305
1924	50494	138	2000	51	100153
1925	57836	158	1660	27	114716
1926	62115	170	1790	50	123203
1927	80552	221	3500	55	159772
1928	57476	157	2600	24	114002
1929	67851	186	2000	37	134580
1930	56663	155	1520	31	112389
1931	42972	118	2000	23	85234
1932	113539	310	7000	32	225201
1933	57343	157	1200	47	113738
1934	39561	108	681	28	78468
1935	71356	195	1010	51	141532
1936	59851	164	1000	50	118713
1937	106973	293	1920	56	212178
1938	102292	280	5000	48	202893
1939	61119	167	3500	53	121228
1940	62287	170	1500	53	123544
1941	124476	341	2340	65	246894
1942	87514	240	1630	62	173581
1943	65442	179	749	47	129802
1944	71758	196	1070	54	142330
1945	60614	166	844	42	120226
1946	43766	120	301	53	86809
1947	59061	162	1040	53	117146
1948	46388	127	480	41	92009
1949	60119	165	900	60	119244
1950	51158	140	948	51	101470
1951	38761	106	1040	46	76881
1952	102290	279	2713	70	202889
1953	44045	121	1460	53	87362
1954	56465	155	844	56	111997
1955	46854	128	2110	50	92934
1956	40123	110	977	49	79583
1957	49099	135	671	57	97386
1958	105410	289	2950	67	209078
1959	41755	114	744	57	82820
1960	39375	108	439	45	78099
1961	44885	123	3190	44	89028
1962	66429	182	1540	59	131760
1963	39902	109	1360	40	79144
1964	47228	129	528	58	93675
1965	61582	169	993	60	122146
1966	60719	166	1640	61	120434
1967	81959	225	9670	75	162563



Wtr-Yr	Total	Mean	Max.	Min.	Ac-Ft	(continuation)
1968	69082	189	802	82	137022	
1969	125821	345	3460	67	249562	
1970	52961	145	950	73	105047	
1971	48891	134	948	60	96974	
1979	136356	374	4230	60	270458	
1980	142561	390	3000	73	282765	
1981	57595	158	1090	71	114238	
1982	63117	173	745	74	125191	
1983	140978	386	1900	63	279626	
1984	62330	170	735	62	123630	
1985	77230	212	880	52	153183	
1986	58599	161	689	58	116229	
1987	49687	136	456	45	98563	
1988	65055	178	1360	71	129049	
1989	40745	112	482	52	80825	
1990	34925	96	397	47	69280	
1991	40309	110	539	49	79960	
1992	49955	136	654	56	99090	
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Avg.	73423	201	2113	56	145633	

**09406150 - LA VERKIN CREEK NEAR LA VERKIN, UTAH**

Wtr-Yr	Total	Mean	Max.	Min.	Ac-Ft
1986	4318	12	112	0.52	8565
1987	2625	7.2	58	0.60	5207
1988	5196	14	180	0.52	10306
1989	1953	5.4	49	0.22	3874
1990	2087	5.8	88	0.49	4141
1991	2287	6.3	126	0.30	4538
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Avg.	3078	8.5	102	0.44	6105





